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December 1981
Mitigation of Training Noises From Ranges

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USE OF AQUEOUS FOAM TO MITIGATE DEMOLITIONS NOISE

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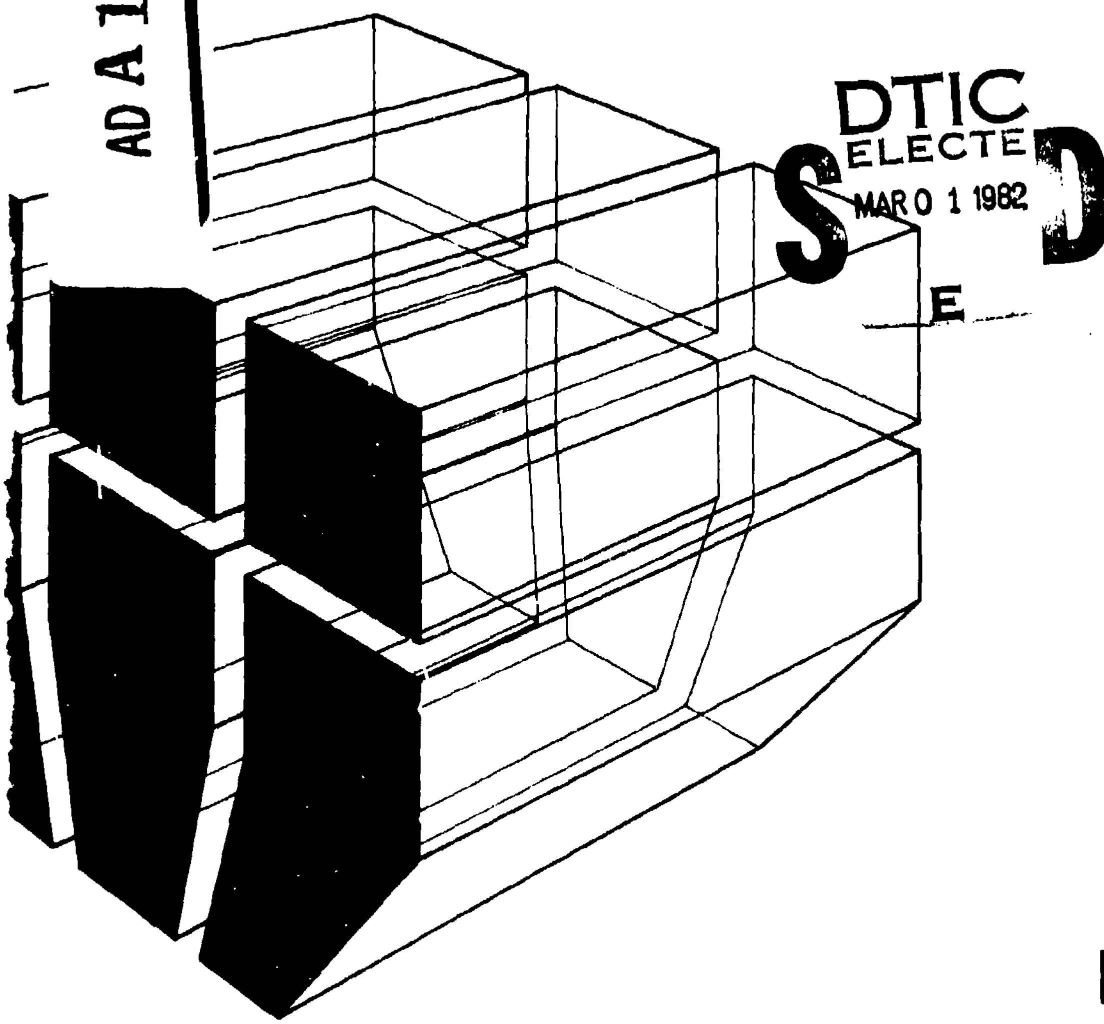

by
Richard Raspet

CERL

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This report describes an investigation into whether aqueous foam is a viable technique for quieting unconfined explosives and whether design parameters can be established for its use to reduce the environmental noise levels of Army artillery, demolition, and explosives ordnance disposal.

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It was concluded that:

(1) Both high- and low-expansion ratio foams can be used to reduce the blast noise levels of Army explosive charges. For unconfined explosives, it was found that blast noise can be reduced by up to 14 dB; if the explosive is confined, the foam's effectiveness is increased by about 3 to 6 dB.

(2.) It is possible to predict the blast noise level reductions for unconfined charges produced by different foams, foam depths, and charge masses and to estimate reductions for confined explosions produced by different foams, foam depths, and charge masses.

(3) Aqueous foam can be used to reduce the blast noise levels of shaped charges and artillery.

FOREWORD

This research was conducted for the Directorate of Military Programs, Office of the Chief of Engineers (OCE) under Project 4A76270A896, "Environmental Quality for Construction and Operation of Military Facilities"; Task E, "Source Reduction, Control, and Treatment"; Work Unit UJ1, "Mitigation of Training Noises from Ranges." The QCR No. is 3.01.006. Mr. G. Velasco, DAEN-MPE-I, is the OCE Technical Monitor.

The work was performed by the Environmental Division (EN), U.S. Army Construction, Engineering Research Laboratory (CERL). Dr. R. K. Jain is the Chief of CERL-EN.

Appreciation is expressed to the following persons for their help during this study:

Dr. Larry Pater of the Naval Surface Weapons Laboratory for sharing information he gained during his experiments on quieting guns with aqueous foam.

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Dr. D. Keefer of the University of Tennessee Space Institute for providing valuable insights into the mechanism of blast attenuation by foam.

M. L. Scala for organizing this material and for her suggestions which led to a clearer understanding of the scaling law for different foam densities.

COL Louis J. Circeo is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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USE OF AQUEOUS FOAM TO MITIGATE DEMOLITIONS NOISE

1 INTRODUCTION

Background

Blast noise from artillery, demolition, and explosives ordnance disposal (EOD) can cause major environmental noise problems if an Army installation's space limitations require that these activities be conducted near populated areas. At some installations, annoyance and damage complaints (from both on and off the installation) have restricted blast-noise-producing training and EOD activities to daytime/favorable weather operations. If the noise produced by such activities could be reduced at the source, then such operations would not have to be curtailed. Thus, the U.S. Army Construction Engineering Research Laboratory (CERL) is studying ways to mitigate the blast noise produced by Army artillery, demolition, and EOD activities.

Purpose

The purpose of this study was to determine whether aqueous foam is a viable technique for quieting unconfined explosives and to establish design parameters for its use.

Approach

This study had six steps:

1. A literature and telephone search (Chapter 2).

2. Experiments to determine if aqueous foam could produce sizable reductions in blast noise (as opposed to blast overpressure) (Chapter 3).

3. Experiments to relate the amount of foam over the explosives to the reduction in C-weighted sound exposure level (CSEL), flat-weighted sound exposure level (FSEL), and peak level. Both high- and low-expansion ratios of aqueous foam were considered* (Chapters 3 and 4).

4. Development of recommended design parameters (Chapters 5 and 6).

5. Experiments to determine if foam is as effective in quieting shaped and cratering charges as it is for quieting bare charges above ground (Chapter 7).

6. Experiments to determine if foam is effective in quieting artillery (Chapter 8).

Scope

This study primarily considered unconfined explosives.

Mode of Technology Transfer

The results of this study will be incorporated into a Technical Bulletin on Noise Mitigation.

2 LITERATURE AND TELEPHONE SEARCH

Three types of experiments pertinent to CERL's blast noise reduction investigation have been reported in the literature:

1. Work with foam-filled shock tubes*[1-4]

2. Work with explosives under foam[5-8]

3. Work with foams to reduce artillery blast noise.[4]

In the first type of experiment, relatively small attenuations are measured and the effect of the foam surface is found to be large. In the second type of experiment, reductions in overpressure by factors of 10 are common. This second class of experiment is much closer to the problem of mitigating Army blast noise, since the pressures from explosives are much greater than the pressures in shock tubes.

Various mechanisms have been advanced as possible causes of overpressure reduction in foam. These mechanisms fall into two classes: direct energy reduction and shock attenuation. Three mechanisms have been proposed which fit the class of direct reduction:

1. The cooling of the explosives' fireball by the water content of the foam. That is, some of the explosive energy goes into vaporizing the foam, cooling the fireball.[6, 7]

2. A direct energy reduction caused by the foam's interference with the afterburn of the explosives.[6, 9]

3. Momentum transferred to the liquid content of the foam; that is, some of the explosive energy goes into accelerating the foam surfaces.[10] It is thought

*Expansion ratio is the ratio of foam volume to fluid volume.

*References are listed on p 37.

that if the mass surrounding the explosives is accelerated, this energy will be regained by the shock wave later and, in fact, may make the explosives more efficient.[11]

In the class of shock attenuation, the literature mentions the following possible mechanisms:

1. **Surface tension effects.** The surface tension energies involved in deforming the surface are rather small, much smaller than the energy reductions observed in explosives. Thus, this is probably not an important mechanism.[6]

2. **Reflections from the bubble surfaces.** Multiple reflections from the foam surfaces could cause the shock wave to stretch out or diffuse. In this case, there would be no loss of impulse, just a lowering of shock wave peaks. Once the pulse left the foam, it is hypothesized that the wave would again shock up and little energy would be lost.[12]

3. **Lowered sound velocity.** Shock tube experiments have recorded a much lower sound velocity in foams. This lowering of the velocity causes the shock wave to disperse and would lower the peak overpressure. Again, it is possible that the wave could shock up after leaving the foam.[1, 3, 5]

4. **Higher heat capacity materials.** The presence of higher heat capacity materials during the expansion of the blast wave could result in more waste energy and, thus, in a reduction in overpressure.[13]

Blast Overpressure Reduction Experiments

Three groups have performed experiments pertinent to the problem of quieting Army blast noise: (1) J.S. de Krasinski of the University of Calgary, Canada, (2) F. H. Winfield and D. A. Hill of the Defense Research Establishment, Canada, and (3) D. A. Dadley, E. A. Robinson, and R. C. Pickett of the Royal Armament Research and Development Establishment, UK. Figure 1 shows the results of de Krasinski's field experiments, a plot of pressure vs distance for 10 g of PETN with a No. 6 Seismocap. The foam used in these experiments was Palmolive Rapid Shave, which has a void fraction of 0.936 (the void fraction is the volume of gas contained in the foam divided by the total volume of the foam). The reduction in pressure at 0.06 m was from 495 to 130 psi (3413 to 896 kPa), or a factor of almost 4 in overpressure (12 decibels [dB]). It appears that this reduction is larger at 0.01 m, that is, from 505 to 32 psi (3481 to 220 kPa), or a factor of 16 (24 dB). For this particular experiment, the reduction increased with distance through the foam.

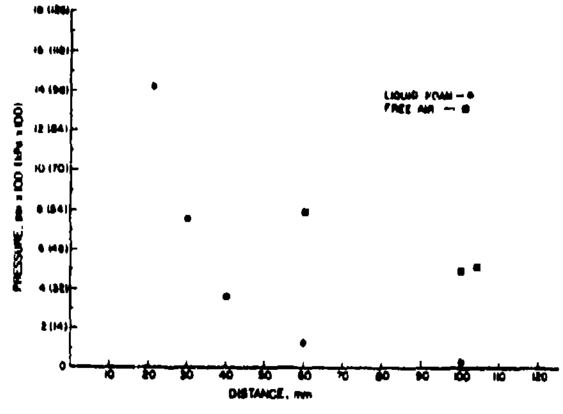
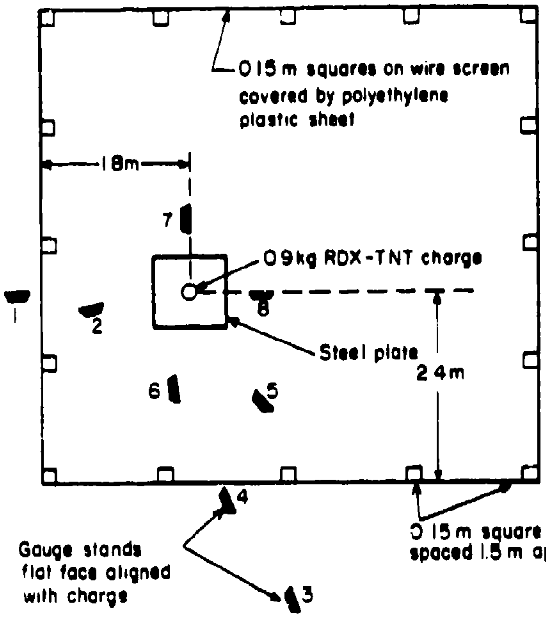


Figure 1. Pressure vs distance for 10 g of PETN with a No. 6 Seismocap (from W. Anson and J. S. de Krasinski, *Field Experiments in the CIL Facilities of the University of Calgary*, Report No. 76 [University of Calgary, Canada, March 1976]).

F. H. Winfield and D. A. Hill experimented with a 6 × 6 × 1.8 m high enclosure of foam. Pressure transducers were placed both inside and outside the foam (Figure 2).[6] In this experiment, an explosive composed of 0.9 kg of RDX was set off at 0.45 m above ground level. Three different foam bases were used: Chieftain XHX, Rockwood JET-X, and Lorcon Fullex. These foam solutions were used with a Rockwood Super JET-X nozzle. The foams generated had expansion ratios between 100:1 and 200:1. The curves of overpressure vs distance for foam and free air are shown in Figure 3; the curve of positive duration vs distance is shown in Figure 4. Winfield and Hill feel that the fact that the impulse curve has zero slope at about 1.2 m from the charge under foam and at about 1.8 m from the charge in air indicates that the fireball diameter is smaller in the foam. That is, the zero slope region is the area in which the fireball has ceased to grow.

Although pressures of the magnitude found in this experiment are usually displayed in pressure units, for later comparison they have been plotted as decibel reduction vs scaled distance through the foam (Figure 5). The reduction in the foam increases rapidly from 1.0 to 2.0 scaled m, but levels off above 2.0 m. The portion in which the increase is linear has a slope of roughly 14 dB per scaled m.* These measure-

*Explosive data are commonly displayed in terms of scaled dimensions. In cube root scaling, the linear dimensions are divided by the cube root of the charge mass.[17]



LEGEND		
Gauge No	Distance Ft (m)	Pressure / Temperature
1	6 (1.8)	P
2	3 (0.9)	P
3	14 (4.2)	P
4	9 (2.7)	P
5	6 (1.8)	P
6	4 (1.2)	P
7	3 (0.9)	T
8	4 (1.2)	T

* Only used under foam

Figure 2. Layout of pressure and temperature gauges for explosions under foam (from F. H. Winfield and D. A. Hill, *Preliminary Results on the Physical Properties of Aqueous Foams and Their Blast Attenuating Characteristics*, Technical Note No. 389 [Defense Research Establishment, Suffield, Ralston, Alberta, Canada, August 1977]).

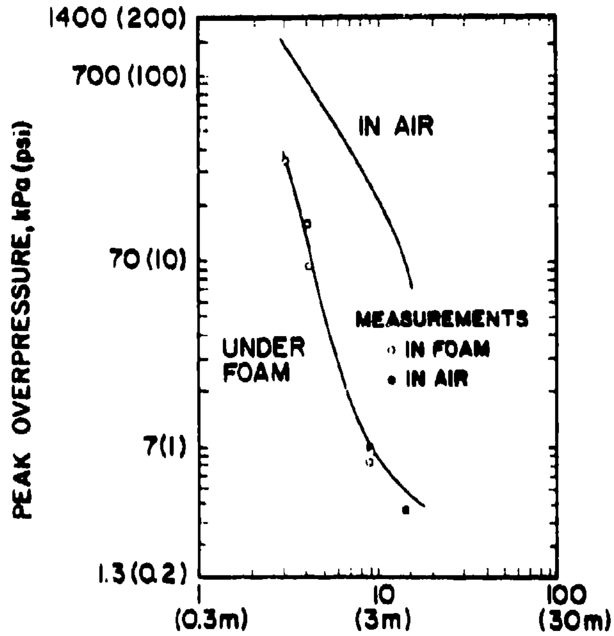


Figure 3. Peak overpressure reduction under foam (from F. H. Winfield and D. A. Hill, *Preliminary Results on the Physical Properties of Aqueous Foams and Their Blast Attenuating Characteristics*, Technical Note No. 389 [Defense Research Establishment, Suffield, Ralston, Alberta, Canada, August 1977])

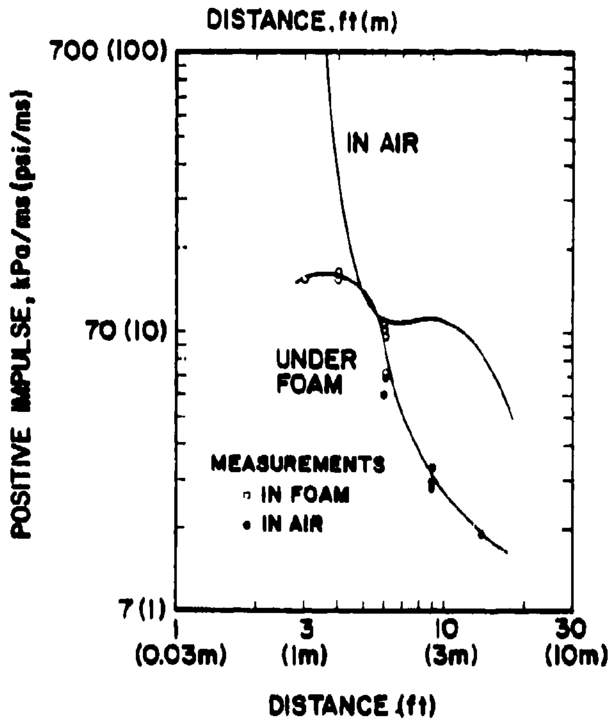


Figure 4. Positive impulse reduction under foam (from F. H. Winfield and D. A. Hill, *Preliminary Results on the Physical Properties of Aqueous Foams and Their Blast Attenuating Characteristics*, Technical Note No. 389 [Defense Research Establishment, Suffield, Ralston, Alberta, Canada, August 1977]).

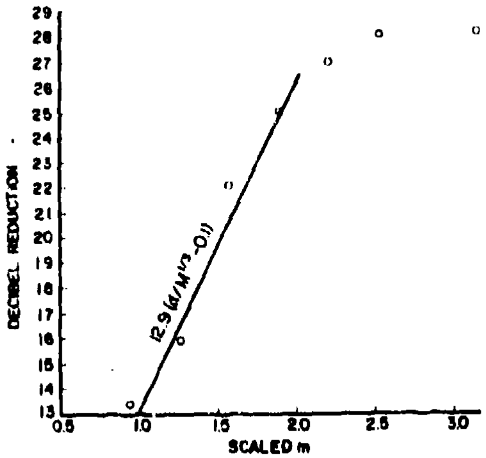


Figure 5. Decibel reduction vs distance through foam. (Plotted from data given in F. H. Winfield and D. A. Hill, *Preliminary Results on the Physical Properties of Aqueous Foams and Their Blast Attenuating Characteristics*, Technical Note No. 389 [Defense Research Establishment, Suffield, Ralston, Alberta, Canada, August 1977].)

ments indicate that the mechanism works directly on the fireball. Winfield and Hill suggest this effect may be caused by the heat of water vaporization, which absorbs the energy in the fireball.

In a similar experiment, Klautt and Hill measured gas temperature after the shock had passed by.[8] They could not measure the fireball temperature directly, but measured the temperature of the gas products after the explosion. The temperatures of these products were reduced from 75 to 37°C at 0.9 m and from 72 to 28°C at 1.2 m away from the explosion. This indicates that the foam either cools the fireball or reduces the size of the fireball from the 1.9 m radius observed in air.

Dadley, Robinson, and Pickett measured the overpressures and impulses from 5 lb (2.27 kg) of RDX/TNT at ground level.[7] The foam was generated by a Turbex generator manufactured by the Angus Fire Armor Company. This foamer produced a foam with a 300:1 expansion ratio. Figure 6 shows the free air levels and the levels under the foam produced during their experiment. In Figure 7, these results have been converted to decibel reduction vs scaled distance. The reduction increases rapidly up to about 2 scaled m, with a maximum reduction of 17dB. The reduction then decreases rapidly.* Note the close agreement between the data of Dadley et al. and those of Winfield et al. when both are plotted vs scaled distance (Figures 5 and 7). Although Dadley et al. give no data about saturation of effectiveness, they report that earlier experiments indicated that the foam is ineffective when its depth is greater than the fireball diameter of $d = 1.5\,(M)^{1/3}$ m, where M is the mass of the explosive in kilograms. They also say that the efficiency of the foam is greatly affected by the standoff distance between the explosives and the foam, although they did not report what magnitude of standoff was investigated.

*Dadley et al. do not say whether the charge was centered in their experimental enclosure; if it was, there was no foam beyond 2 scaled m.

Environmental Noise Reduction Experiments

In 1977, A. K. Clark, P. J. Hubbard, P. R. Lee, and H. C. Woodman of the Royal Armament Research and Development Establishment, UK, published the results of an experiment which measured the reduction in environmental noise which occurred when explosives were fired in test chambers filled with foam.[14] They used a Turbex generator to produce a foam with an expansion ratio of 300:1; foam depth in each of the test chambers was about 2.5 m. Measurements were made of the A-weighted peak level from charges set with and without foam in test chambers. In the larger chamber, the reduction could not be directly compared since charges greater than 0.34 kg could not be fired without foam because of complaints from a neighboring industrial estate. A reduction of about 20 dB for the 0.3 kg charge was measured in the smaller chamber; this reduction was larger for smaller charges in the same chamber (Figure 8). These reductions are certainly significant, but cannot be generally applied because this experiment (1) involved confined explosives only, (2) measured only the A-weighted peak pressure level, and (3) used an indirect path from the explosives to the sound-level meter.

The Naval Surface Weapons Laboratory (NSWL) has done experimental work on the use of foam to reduce gun blast noise.[4] They have performed model studies to optimize the shape of the cannister containing the foam. A full-sized test was done using a 5-in./54 Naval weapon. A cylindrical cannister was constructed 10 calibers in length and 5 calibers in diameter. This cannister had a central baffle (Figure 9). The cannister was filled with a low-expansion foam with an expansion ratio of about 10:1. The foam was produced by a Mearl OT-10 foam mixing tank and a nozzle constructed at the NSWL. When the cannister was empty, it produced about a 3-dB reduction in peak pressure; when the cannister was filled with foam, it produced a 14-dB reduction in overpressure.

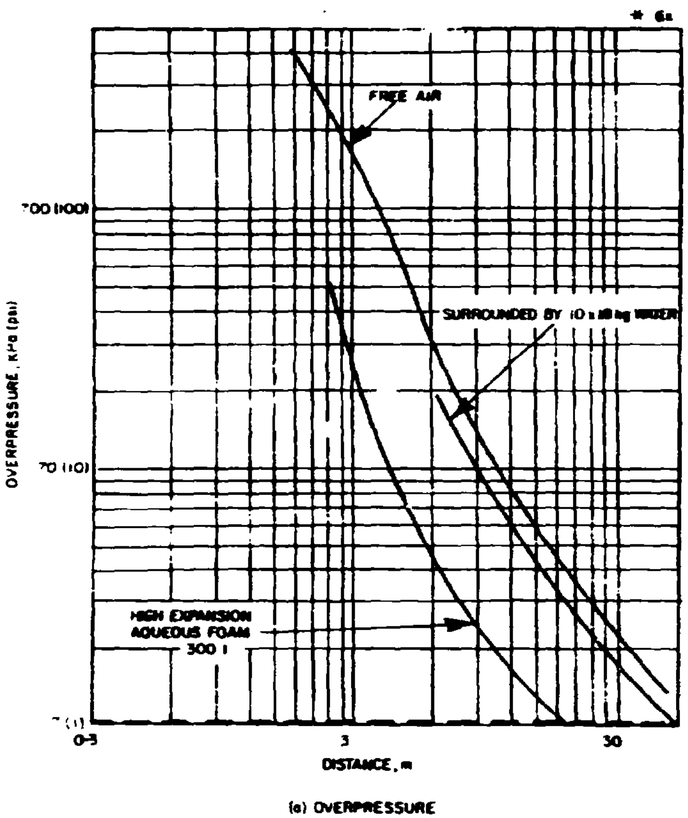


Figure 6. Overpressure vs distance through foam; data scaled to a charge weight of 18 kg (from D. A. Dadley, E. A. Robinson, and V. C. Pickett, *The Use of Foam to Muffle Blast From Explosion,* Paper presented at the IBP-ABCA-5 Meeting [June 1976]).

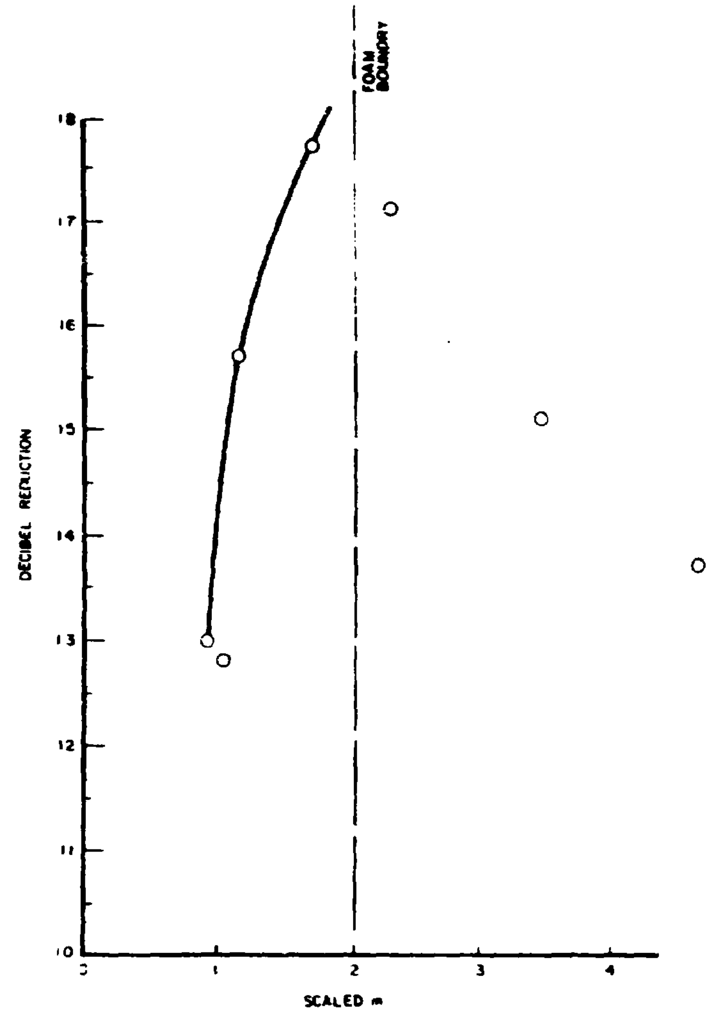


Figure 7. Decibel reduction vs scaled distance through foam. (Plotted from data given in D. A. Dadley, E. A. Robinson, and V. C. Pickett, *The Use of Foam to Muffle Blast From Explosion,* Paper presented at the IBP-ABCA-5 Meeting [June 1976].)

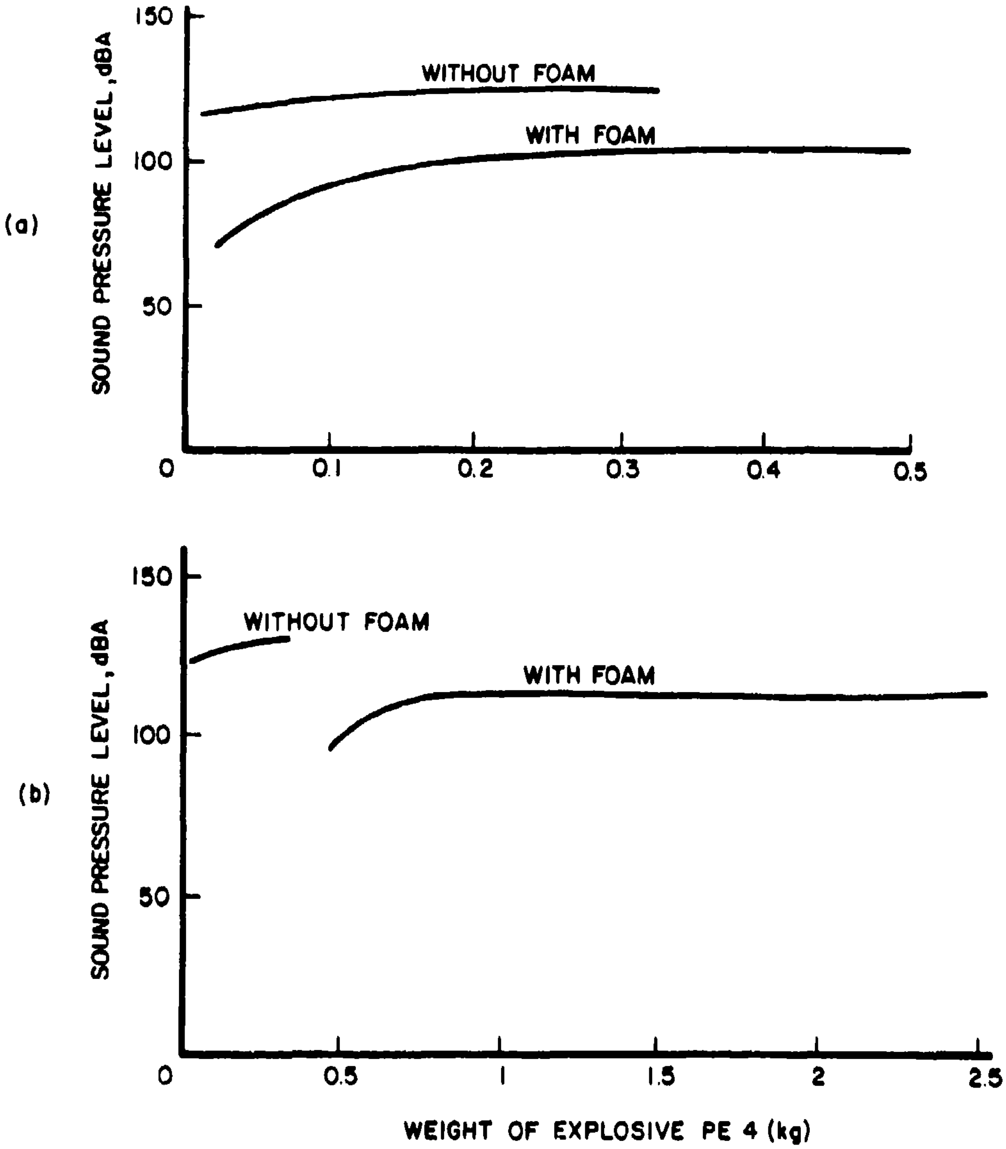


Figure 8. Plots of sound pressure level vs charge weight for the small (a) and large (b) chambers described in A. Y. Clark, P. J. Hubbard, P. R. Lee, and H. C. Woodman, "The Reduction of Noise Levels for Explosive Test Facilities Using Aqueous Foams," *Proceedings of the Second Conference on the Environmental Effects of Explosives and Explosions,* NSWC/WOL TR 7-36 (Naval Surface Weapons Laboratory [NSWL], July 1977).

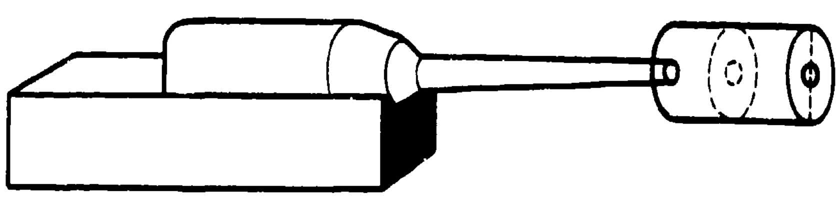


Figure 9. NSWL system for gun noise reduction.

3 MEASUREMENT OF THE REDUCTION OF BLAST NOISE BY HIGH-EXPANSION AQUEOUS FOAM

Test and Analysis Approach

To determine if high-expansion foam can be used to quiet unconfined explosives, CERL performed four tests to relate the amount of high-expansion foam to the reduction in CSEL, FSEL, and peak level reductions produced by the foam. Data from these tests were then used to develop foam scaling laws.

Test 1 was a feasibility test which considered a very limited number of charge sizes. In this test, charges were fired in (1) pits filled with foam and (2) enclosures constructed of plastic sheeting supported by corner posts. Test 1 results are given in Table 1.

Test 2 investigated the effects of different amounts of foam on CSEL, FSEL, and peak levels. Two charge sizes were used. The noise level reductions vs depth of foam were then plotted for two different charge sizes (Figure 10).

Test 3 kept the foam depth constant, but varied the charge size. These reductions are plotted vs cube-root-scaled foam depth in Figure 11. The foam depth used in this plot is the geometrically averaged foam depth:

$$d = \frac{\sqrt{\ell \times w \times h}}{2} \qquad \text{[Eq 1]}$$

where: ℓ, w, h are the foam dimensions in meters.

When the results of Test 1 were compared with the results of Tests 2 and 3, it was apparent that much larger reductions were achieved using the pit configuration in Test 1. Thus, a fourth test was performed to determine whether the results of Test 1 or those of Tests 2 and 3 were more representative of the effect of foam on CSEL, FSEL, and peak level. All data from Tests 1 through 4 are plotted vs scaled foam depth in Figure 12.

Experimental Setups and Procedures

CERL tested two types of configurations. Spheres of C-4 plastic explosive were used as the explosive charge. During all tests, the C-4 charges were set in pairs: a test charge under the foam and a reference charge without foam. All charges were set on crushable posts to eliminate energy variations caused by coupling into the ground.

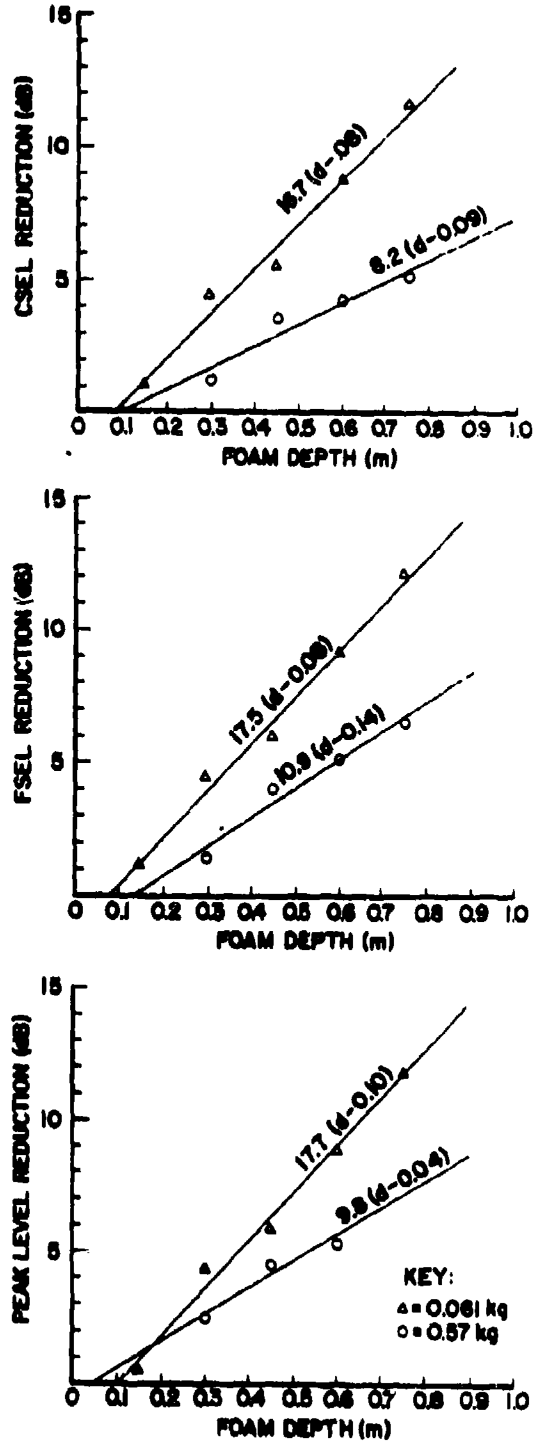


Figure 10. CSEL, FSEL, and peak level reductions vs foam depth (Test 2).

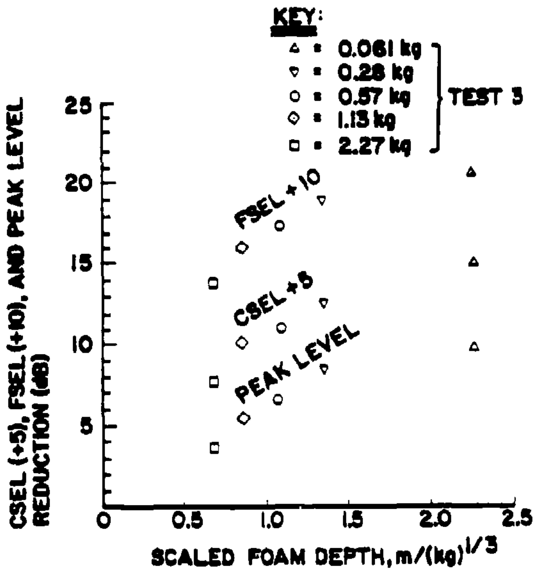


Figure 11. CSEL, FSEL, and peak level reductions vs scaled foam depth (Test 3).

All experiments described in this chapter used a National Foam System WP-25 High-Expansion Foamer with a National 1½ Percent High-Expansion Foam solution. When water was provided by a fire truck at pressures of 200 to 250 psi (1379 to 1723 kPa), foam with an expansion ratio of 250:1 was produced.

Test 1

The first test used 0.57 and 2.27 kg of C-4 explosive; each charge was mounted on a 0.6 m high post. Microphones were placed on either side of the explosives at 150 and 300 m. The noise levels were measured *in situ* with Bruel and Kjaer 4921 outdoor microphone units and the CERL-designed and -constructed True-Integrating Environmental Noise Monitor and Sound-Exposure-Level Meter.[15] The signal was recorded on Nagra S-J recorders for later laboratory analysis.

Two configurations were used during Test 1:

1. **Pit Configuration.** The test charges were set in a 3.0 × 3.0 × 1.75 m pit and foam was piled about 0.3 m above ground level, covering the charge with 1.45 m of foam.

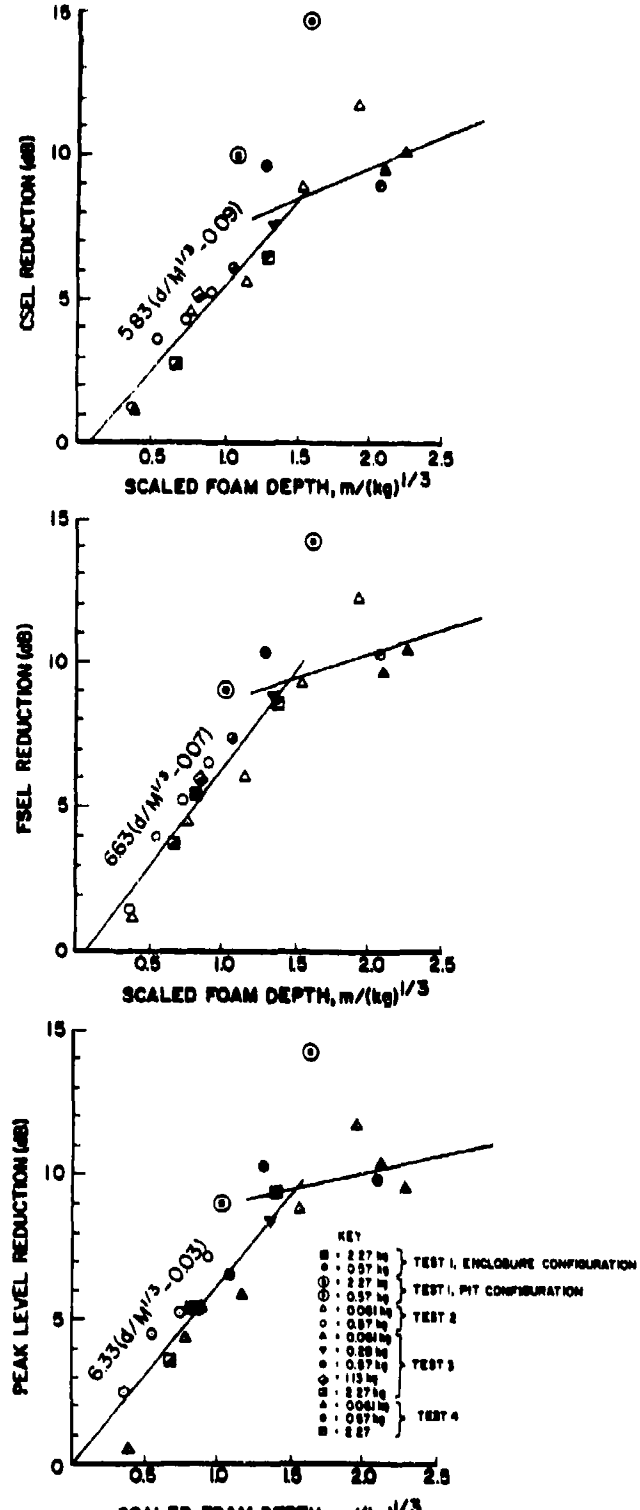


Figure 12. CSEL, FSEL, and peak level reductions vs scaled foam depth (Tests 1 through 4).

2. **Enclosure Configuration.** The foam was supported above ground level by a fence of reinforced plastic sheeting stapled to corner posts to form a 2.4 × 2.4 × 1.7 m high volume.

The results of Test 1 established that significant environmental noise reductions could be achieved; these reductions were similar for all metrics measured, but did not provide enough information to allow foam thickness and charge size to be related to a reduction in sound pressure levels (Table 1).

Test 2

For Test 2, charges were set at the center of a cubical volume of foam supported by plastic sheeting attached to corner posts. Two Bruel and Kjaer 4921 microphones were placed 60 and 120 m away from and on either side of the enclosure. Two test series were run in which the charge size was constant: 0.57 and 0.061 kg. The enclosure's dimensions varied from 0.305 to 1.52 m in 0.305 m steps. The foam dimension used to plot the data was the shortest distance from the charge to the foam surface (Figure 10). These plots show that the data for each charge size are linear within the accuracy of the data. The smaller charges display larger reduction.

Test 3

A third series of tests was performed in which the foam dimensions were held constant, but the charge weights were varied. Charge weights of 0.061, 0.28, 0.57, 1.13, and 2.27 kg were fired in a 1.8 m enclosure. Because the wind tended to knock the foam down by 0.08 to 0.150 m during the tests, the geometric averages of 1.8, 1.8, and 1.6 were used as the foam depth. This depth was then cube-root-scaled and the reductions plotted against the scaled foam depth (Figure 11). The reductions increase linearly up to about 1.2 scaled m, but then appear to level off, much as Winfield and Hill described.[8]

Test 4

A fourth experiment was performed to determine whether the data from Tests 2 and 3 (which appeared to level off at about a 10-dB reduction) or the Test 1 pit configuration data (which achieved reductions of 14 dB) represented the best data for a design curve for unconfined explosions. Test 4 considered:

1. A 0.061-kg C-4 charge set off in a 1.63 × 1.63 × 1.52 m enclosure. Microphones were placed at 15 and 30 m—closer to the charge than in Tests 2 and 3—to determine if a propagation difference could be the cause of the saturation.

2. A 0.57-kg C-4 charge centered and set off in a 3.66 × 3.66 × 3.66 m enclosure.*

*These tests were used to determine the behavior of larger charges for large scaled foam depths.

Table 1

Average Difference in Sound Pressure Levels Between Reference Charge and Test Charge

Type of Event	FSEL (dB)		Peak Level (dB)		CSEL (dB)
	152 m	304 m	152 m	304 m	152 m
0.57 kg (pit without foam)	0.38	0.23	1.91	2.08	1.85
0.57 kg (pit with foam)	14.4	13.8	13.9	13.6	14.6
0.57 kg (enclosure with foam)	10.4	10.2	9.6	11.1	9.6
2.27 kg (pit with foam)	9.0	9.0	10.2	8.9	10.0
2.27 kg (enclosure with foam)	5.0	5.9	5.5	5.2	6.6

3. A 2.27-kg C-4 charge centered and set off in a 3.66 × 3.66 × 3.66 m enclosure.*

The first series occurred during light winds; two trials were run. The second and third series occurred in fairly strong winds and the variation from microphone to microphone was rather large; i.e., the standard deviation was 3 dB.

Data Analysis

All data from Tests 1 through 4 were plotted vs scaled foam depth (Figure 12). The foam depths in these plots are the geometric average foam depths or their equivalent. The data lines are least squares fit to all the data, except the data from the pit configuration, Test 1. The first segment of the line is fitted to the data points from 0.0 to 1.6 scaled m, the second segment to points from 1.2 to 2.5 scaled m.

From Figure 12 it is apparent that:

1. All the data obey the cube-root-scaling laws, with the exception of the data taken in the pit during Test 1. That is, all of the data lie within 2 dB of the best fit line; the scatter is greater above 1 scaled m.

2. For unconfined explosives, the reduction was limited to about 10 dB. There appears to be a transition from large attentuations up to 1.4 scaled m to a much smaller attenuation above 1.4 scaled m. This saturation effect was reported by Dadley et al. for foam depth greater than the scaled fireball diameter of 1.5 scaled m.[7] Although there is not agreement as to where the effectiveness is reduced, these results agree qualitatively.

3. The measurements made during the pit configuration tests display a greater reduction than similar measurements made during the enclosure configuration tests. These measurements are 3 to 6 dB above the best fit line. This occurs because the relative confinement of the pit walls increases the effectiveness of the foam, either by preventing the foam from being blown away from the fireball or by reflecting pulses so they make more than one pass through the foam. This result also lends credence to the large reductions reported by Clark et al. for charges completely confined in explosive test chambers.[14]

4. Winfield and Hill's data were scaled out to 61 m using a design chart of pressure vs distance to provide a comparison of the amount of peak level attenuation which can be achieved by different amounts of foam.[16] This comparison technique is at best crude, since at close ranges energy is still being fed into the shock wave, and the foam certainly must affect these energy transfers. This calculation also neglects the reflection of the shock wave by the foam-air interface.

The result of this calculation is displayed in Figure 13. Winfield and Hill's data do not display a saturation value close to 1.5 scaled m. Considering the difference in foam density (100:1 or 200:1 vs 250:1 or higher) and the difference in technique (in-foam measurements vs remote acoustic measurements), the results agree quite well: 8.6 vs 6.3 dB per scaled m. This difference may be due to the fact that Winfield and Hill's pressure transducers were near the bottom of the foam volume, and therefore were in denser foam, while CERL measured the average release of energy in all directions.

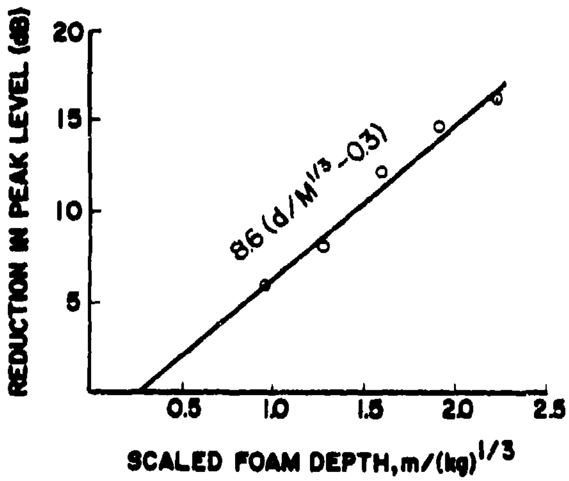


Figure 13. Peak level reduction vs scaled foam depth (Calculated from Winfield and Hill data).

Although Winfield and Hill do not display a saturation value for overpressure reduction, they do note the point at which their positive impulse vs distance curve has zero slope is shifted from 3.0 to 1.2 m by the foam. They felt that this implied that the foam reduced the fireball's size.

5. All metrics (CSEL, FSEL, and peak level) are reduced by roughly the same amount. The slopes are 5.83, 6.63, and 6.33, respectively, per scaled meter. That the difference between the peak level slope and the FSEL slope is small indicates that there is little duration change in the wave form, since the FSEL is

*These tests were used to determine the behavior of larger charges for large scaled foam depths.

an integral over the duration of the wave. The positive durations and total durations of waves with and without the foam were also measured (Figure 14); the duration usually was slightly reduced. Figures 15 and 16 show the percentage reductions vs scaled depth of foam.

The positive duration reductions (about 5 percent) display no significant trends when plotted vs scaled foam depth. The total durations display great scatter, but there is a definite tendency for the duration change to become smaller as the amount of foam increases. This indicates the presence of two mechanisms: (a) a direct reduction of energy or of time of burn, and (b) a dispersive mechanism which spreads the energy over a longer time as the wave travels through the foam.*

6. It appears that the foam does not have to be in contact with the explosive charge to be effective. In a limited experiment, charges of 0.061 and 0.57 kg were set inside a 0.36 m cubicle box centered in the 1.22 m enclosure. Table 2 shows the 1.22 m results with and without the 0.18 m standoff. It appears that while a small scale standoff of about 0.4 scaled m has no noticeable effect, a larger standoff of 0.9 scaled m does reduce the foam's effectiveness. On most of the plots, the X-intercept of the best-fit curve is positive, indicating that the first few inches of foam are relatively ineffective.

4 MEASUREMENT OF THE REDUCTION OF BLAST NOISE BY LOW-EXPANSION RATIO AQUEOUS FOAM

The noise level reductions measured during the experiments described in Chapter 3, although fairly consistent, were limited to about 10 dB. Thus, CERL decided to investigate whether a foam denser than the 250:1 expansion ratio foam used in those tests would produce still larger noise level reductions.

A Mearl Corporation OT 10-5 foamer was selected for the dense foam experiments. The foamer's nozzle was adjusted so it would generate a relatively stiff 30:1 expansion ratio foam at a reasonably high flow rate; the foam was made from a 5 percent solution of

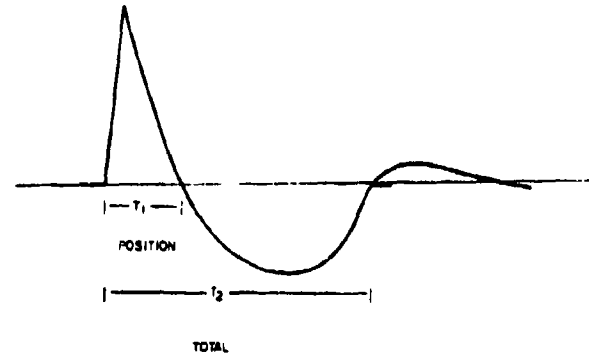


Figure 14. Durations measured from wave forms.

Table 2

Standoff Experiment Reductions

Charge Mass (kg)	CSEL (dB)	FSEL (dB)	Peak (dB)
0.57	4.2	5.2	5.3
0.57 standoff	4.6	5.4	5.5
0.061	8.8	9.2	8.8
0.061 standoff	5.9	6.5	6.5

National Foam System 1½ Percent High-Expansion Foam detergent.

The experimental setup for the 30:1 foam tests was similar to the one described in Chapter 3 for the 250:1 foam tests. Spherical charges of C-4 were set in pairs, one in the foam and one outside the foam. The charges were set on crushable posts so they were centered in a near-cubical enclosure of plastic film (to support the foam). Microphones were placed on either side of the enclosures 61 and 122 m from the center. Noise levels produced by charges with and without foam were measured using the CERL True-Integrating Environmental Noise Monitor and Sound-Level Meter. The signals were recorded on an Ampex 2230 14-track FM recorder. CSEL, FSEL, and peak level were measured.

Three charge sizes were used: 0.11, 0.57, and 2.27 kg. Three enclosure sizes were used with the 0.11-kg charge: 0.31, 0.91, and 1.52 m. Five enclosures were used with the 0.57-kg charge: 0.31, 0.61, 0.91, 1.22, and 1.52 m. Two sizes were used with the 2.27-kg charge: 0.91 and 1.52 m. The enclosures were oversized by 0.2 m on length and width. The foam depth used to

*A reduction in time by 20 percent corresponds to about a 1-dB greater attentuation of FSEL than of peak level. Analysis of the CSEL reduction is complicated by the C-weighting filter. In this case, a decrease in duration decreases the integral over time, but also decreases the reduction produced by the C-weighted filter.

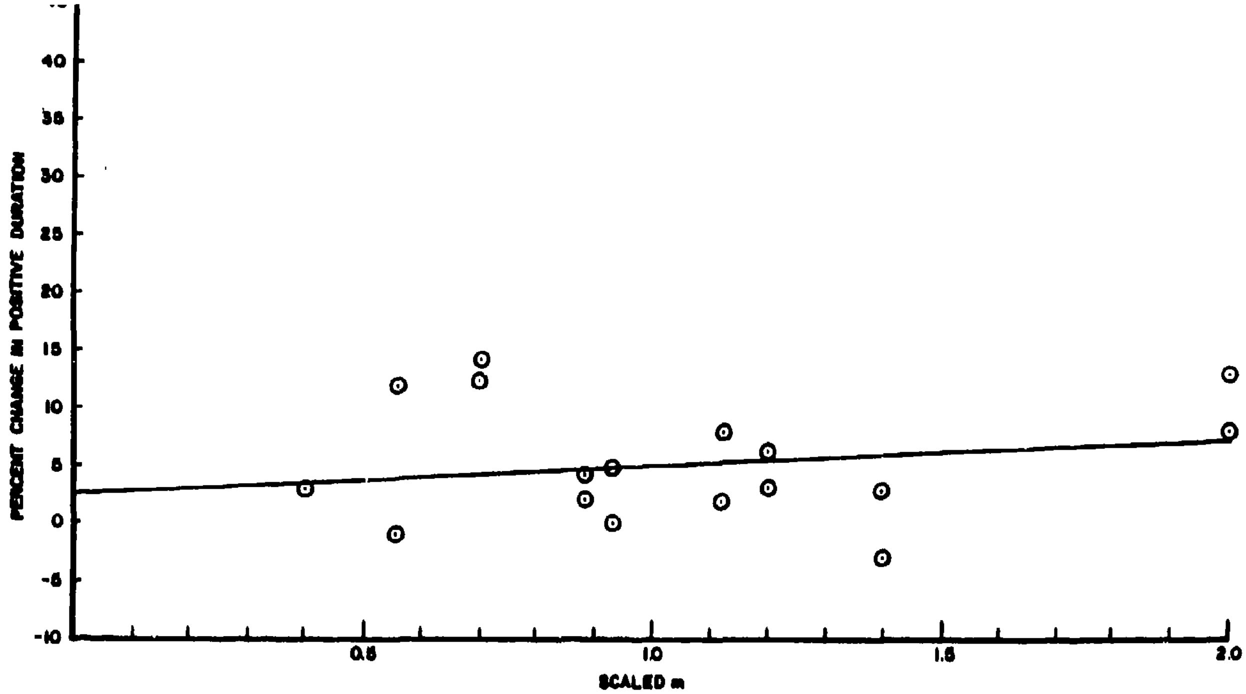


Figure 15. Percent change in positive duration vs scaled foam depth.

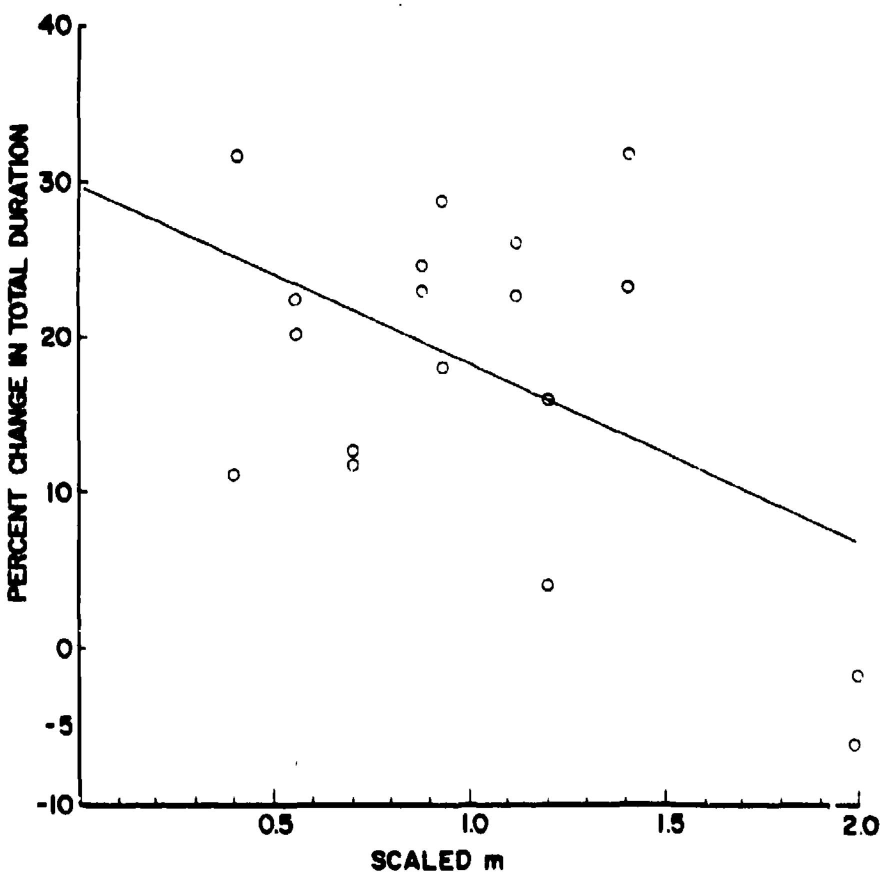


Figure 16. Percent change in total duration vs scaled foam depth.

analyze the results of the low-expansion foam tests was the cube root of the volume divided by 2; that is, the geometric average of the distance from the charge to the foam surface.

The differences in level from the different stations were averaged. These differences are plotted vs cube-root-scaled foam depth in Figure 17, which shows CSEL, FSEL, and peak level reductions produced during the low-expansion foam tests. Three features in Figure 17 are of interest:

1. The data scaled rather well; all the points lie close to one another when reduced to scaled coordinates. None of the points lies farther than the average standard deviation of 1.1 dB from the fitted lines.

2. The reduction in FSEL is not linear for the full range of scaled foam depth, but has a break point at about 0.80 scaled m. The first segment on the FSEL curve is fitted to the points from 0 to 0.9 scaled m; the second segment is fitted to the points from 0.8 to 1.3 scaled m. As shown in Figure 17, the CSEL has a similar break point near 0.82 scaled m. The peak level reduction does not display as clean a break point. However, the point corresponding to the largest scaled distance is under the curve fitted to the rest of the points. There are two possible explanations for these breaks in the reduction curves:

a. There are two mechanisms for the reduction, one which is only effective at higher pressures and densities, and a weaker effect which can only be observed outside of the strong shock region.

b. There is a single mechanism which produces large attenuations for high-pressure regions and smaller reductions for lower pressure and temperature regions.

The linearity of the curves and the sharpness of the break argue for the first hypothesis since the transition on the figure is rather sharp.

3. As with the high-expansion foam, the low-expansion foam reduced the FSEL more than it reduced the peak level. The initial slope of the peak level curve is about 10.8 dB per scaled m, while the initial slope of the FSEL curve is about 14 dB per scaled m. This is due to the reduction in time duration of the waveforms by the foam (Chapter 3).

To further investigate the characteristics of this reduction, positive and total durations were measured for several of the events. Like the high-expansion

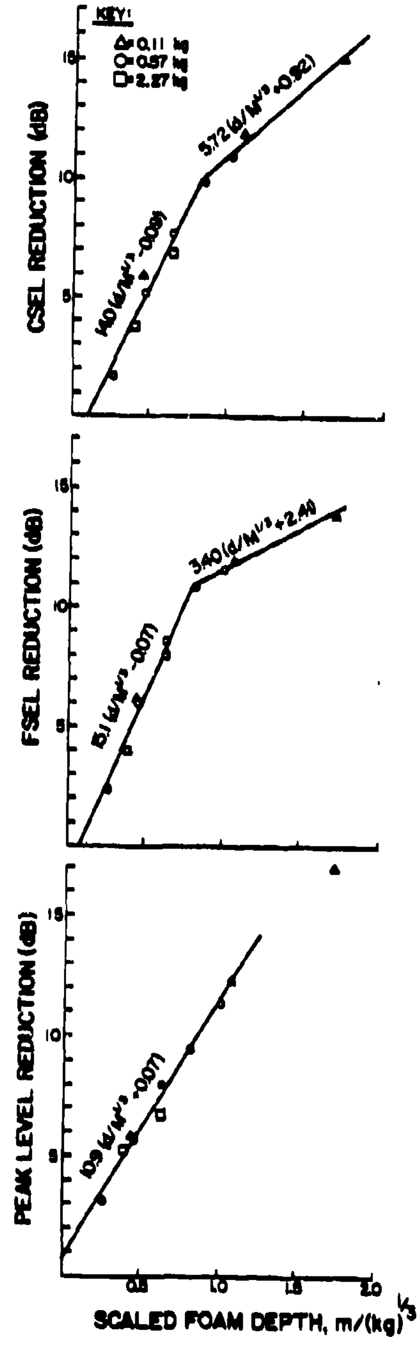


Figure 17. CSEL, FSEL, and peak level reductions vs scaled foam depth: low-expansion foam tests.

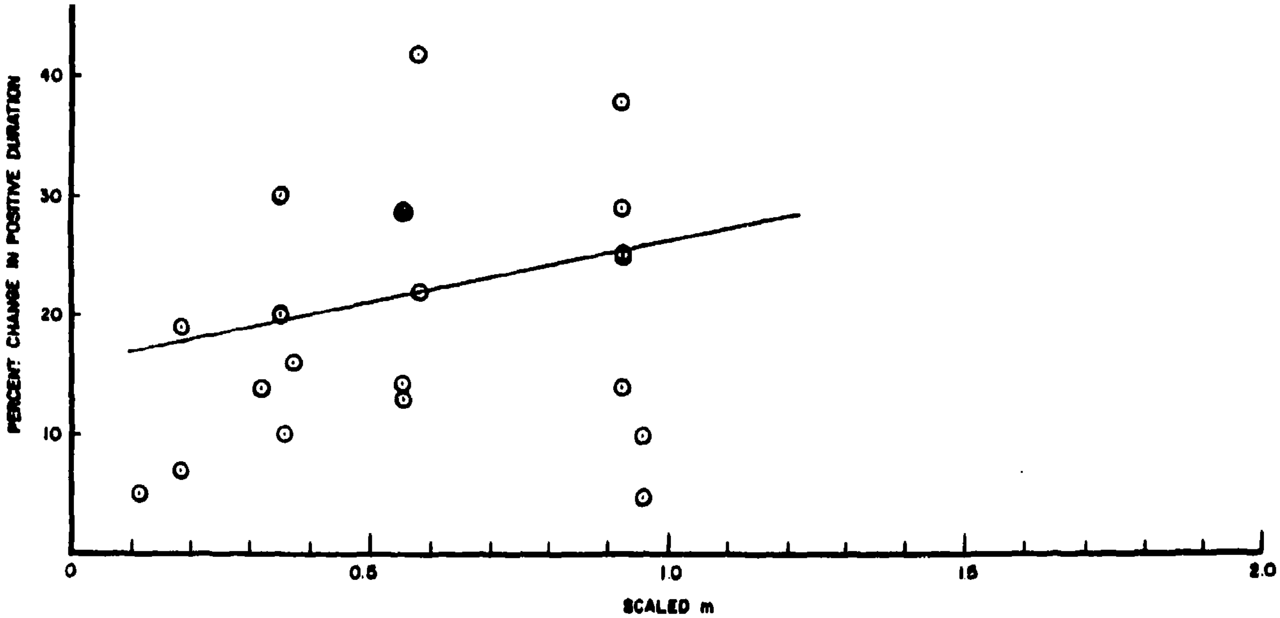


Figure 18. Positive duration reduction: low-expansion foam tests.

foam test data, low-expansion foam data results displayed great variations in duration reductions. The reduction in positive duration was about 20 percent (Figure 18); the reduction in total duration was about 30 percent, with changes scattered down to 0 and up to 44 percent (Figure 19). Even for identical events, the changes varied from 5 to 30 percent. The duration change may be indicative of interference with the length of the burn, or the size of the fireball, or of interference of the foam in the energy transfer from the fireball to the shock wave. There is a small tendency for the duration change to get smaller as the foam depth increases.

A 30 percent reduction in duration corresponds to a 1.5-dB difference between peak and FSEL reduction, if no other change in shape occurs.

5 SCALING LAW ANALYSIS

The work described in Chapters 3 and 4 considered only two different foam expansion ratios: 250:1 (high-expansion ratio foam) and 30:1 (low-expansion ratio foam). For each foam, cube-root-scaled foam depth was used to organize the test results for widely varying charge sizes into a single set of curves for each metric (Figure 12 for the high-expansion foam and Figure 17 for the low-expansion foam). The success in scaling the results for different charge masses in this way indicates that perhaps the two sets of data could be combined if plotted against a scaled variable which includes foam density. To pursue this possibility, the literature on complete blast scaling was examined.

Analysis

Two scaling laws discussed in the literature on complete blast scaling are Sach's scaling and Lampson's earth-shock scaling law.[17] For overpressure, Sach's law states that:

$$\frac{p_1 - p_0}{p_0} = g\left(\frac{p_0 R^3}{E}\right) \qquad \text{[Eq 2]}$$

where:

$g(\ )$ is a function only of $\frac{p_0 R^3}{E}$

p_0 is the ambient pressure

R is the distance from the center of the charge

E is the formally released explosive energy.

Lampson's earth-shock scaling law states:

$$\frac{p_1 - p_0}{p_0} = h\left(\frac{\rho_0 R^3}{M}\right) \qquad \text{[Eq 3]}$$

where:

$h(\ )$ is a function of $\frac{\rho_0 R^3}{M}$

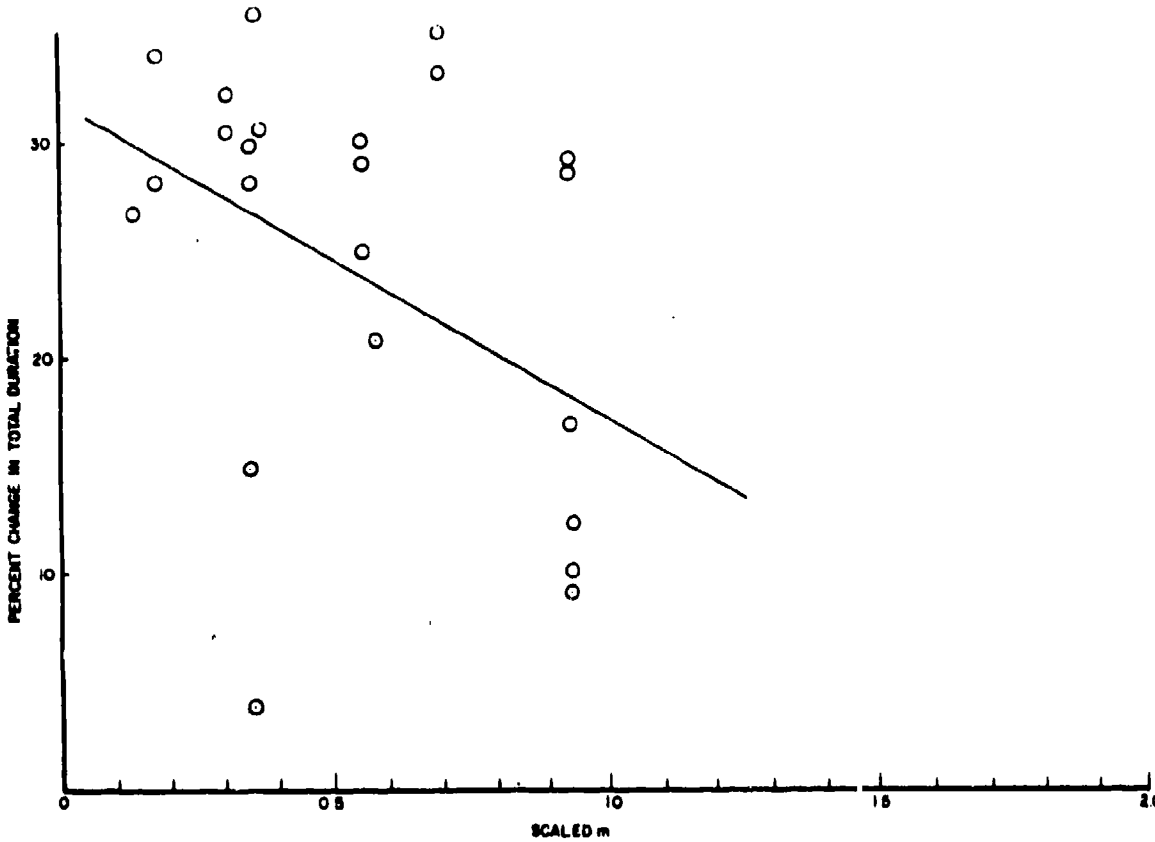


Figure 19. Total duration reduction: low-expansion foam tests.

ρ_o is the density of the medium surrounding the charge

R is the distance from the center of the charge

M is the mass of the charge.

Since the reduction data in Chapters 3 and 4 scaled well as a function of $(d^3/M)^{1/3}$, Lampson's scaling law suggests that plotting all of the data as a function of $\rho d^3/M^{1/3}$, where ρ is the foam density, should be examined.

All of the data points from Chapters 3 and 4, except the data taken using the pit configuration, are plotted vs dimensionless foam depth (Figure 20). The dimensionless foam depth used in this figure is the geometrically averaged foam depth multiplied by the cube root of the foam density in kilograms per cubic meter and divided by the cube root of the charge mass in kilograms of TNT*:

$$X = \frac{\rho^{1/3} d}{M^{1/3}} \quad \text{[Eq 4]}$$

where:

ρ is the foam density in kg/m^3

d is the geometrically averaged foam depth

M is the mass of explosive in kilograms of TNT.

The density of the foam is given by the density of water (1000 kg/M^3) divided by the expansion ratio.

Results

1. The data scale well for all metrics up to a dimensionless depth of 2.5. Little or no systematic differences were detected between the high- and low-expansion foam data. Thus, the foam scaling laws

*When charge mass is used in scaling laws, it is common to express it in terms of an equivalent mass of TNT. The C-4 used in CERL's experiments is about 1.34 times as effective as TNT; to agree with scaling conventions, CERL's charge masses were adjusted by that factor.[18]

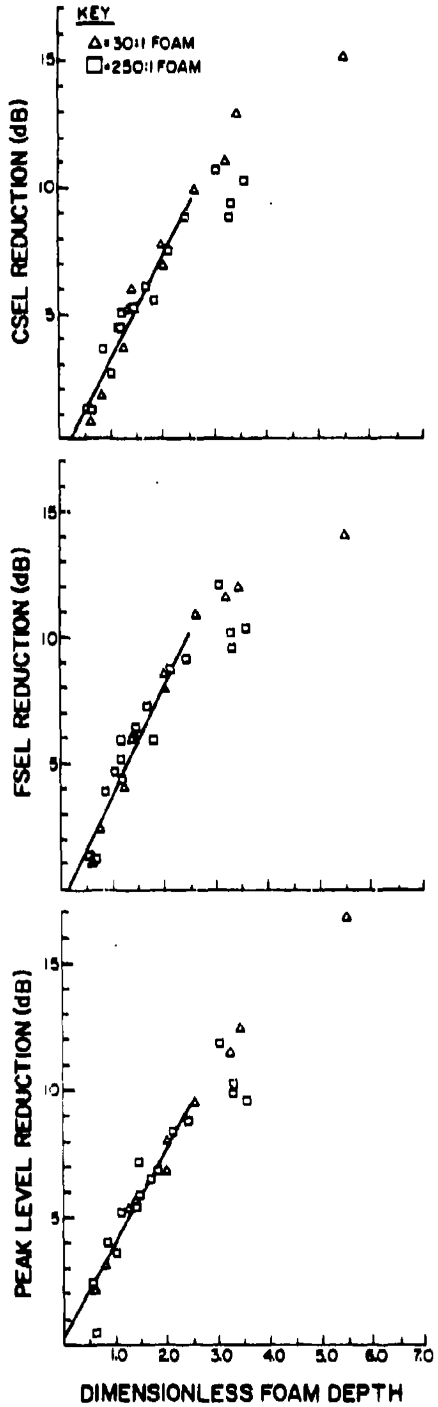


Figure 20. CSEL, FSEL, and peak level reductions vs dimensionless foam depth.

and Figure 20 can be used to predict the reduction produced by different foams, different foam depths, and different charge masses. However, there are not enough data at different foam densities to prove that the foam scaling laws hold for widely varying foam densities. Caution should be used in extrapolating beyond the limits of 250:1 and 30:1. For example, for the extreme case of pure water (expansion ratio 1:1), the foam scaling laws do not hold. When CERL measured the reductions produced by pure water by setting a 0.57-kg charge of C-4 in the center of a 0.39 m cube of water, the dimensionless foam depth calculated for this experiment was 2.22, which by Figure 20 would result in reductions of 8.0, 8.7, and 8.2 in CSEL, FSEL, and peak level, respectively. The actual reductions were 3.8, 3.7, and 5.7 (these were the average reductions measured by microphones at 30.5, 61.0, and 122 m, respectively).

2. If the foam density scaling laws are valid, they would imply that the blast reduction mechanism is the transfer of momentum and energy to the mass content of the foam. In most cases, additional mass around an explosive increases its efficiency; some of the energy is transferred to the mass, which in turn transfers energy into the shock wave.[11]

For foam, however, there is a radical change in the physical distribution of the mass during each energy transfer process. During the energy transfer to the foam, the liquid content is arranged in easily accelerated thin layers. When energy is transferred back to the shock wave, the liquid content is in small, more compact water droplets. If this model is correct, energy is easily transferred to the foam, but only a small portion is transferred back to the shock wave. This model would also explain the decreased effectiveness of pure water with respect to foam, since the transfer of momentum and energy to the liquid content would be more favorable for the thin layers of water in the foam than for the homogeneous mass of water. However, the only way to establish confidently the validity of the foam scaling laws is to make pressure measurements in the foam during an explosion.

3. The foam scaling laws do not hold for dimensionless foam depths greater than 2.5. Above 2.5, denser foam produces greater reductions than lighter foam. This is an indication that there are two mechanisms for the reduction, one which is dominant close to the charge, another which is dominant farther out. The reductions produced by the close-in mechanism scales with foam density; the reductions produced by the other mechanism do not.

6 APPLICATIONS

The results of the experimental work described in Chapters 3 through 5 can be used to predict the noise level reduction of explosives muffled by foam. For these predictions, the best fit lines of Figure 12 and 17 are scaled to kilograms of TNT (Figures 21 through 23). The foam density scaling laws developed in Chapter 5 can then be used to adjust for different foam densities.

Factors involved in calculating noise level reductions are:

1. The equivalent charge mass
2. The expansion ratio of the foam
3. The depth of the foam.

Equivalent Charge Mass

The data analyses of Chapter 3 and 4 used the charge mass in calculating the scaled foam depth. This procedure is only valid if a single type of explosive is used. To use mass scaling laws for different types of explosives, the mass must be adjusted by multiplying the mass times the relative efficiency of the charge.

The efficiencies of various Army explosives are listed in Table 3. Table 4 lists the equivalent charge masses for some common Army demolitions.[18] (Note that the equivalent charge mass of the booster charge must be added to the cratering charges.)

Foam Depth

The foam depth used in the analyses described in this report is the geometrically averaged foam depth. For the rectangular enclosures, $\sqrt[3]{\ell wh}/2$ was used. This will be a conservative depth for cases where the charge is at the bottom of the foam, rather than centered in the foam. For the charge at the bottom of the foam, $\sqrt[3]{\ell wh}/2$ should be used as the foam depth.

For nonrectangular shapes, the average depth is also the cube root of the volume divided by two. The ideal shape for the foam volume would be a hemisphere (for a charge on the ground) or a sphere (for a charge above ground). In designing enclosures with collapsible walls, the dimensions should be such that the distances from the charge to the foam surface are about equal. For an enclosure with rigid walls (pits or permanent enclosures), the distance to the open area should be the largest dimension (see Figure 24).

Table 3

Efficiencies of Various Army Explosives

Explosive		Efficiency
TNT		1.00
Tetrytol, M1, M2		1.20
Composition C3 M3, M5		1.34
M5A1 Composition C4 M112		1.34
Ammonium Nitrate (cratering charge)		0.42
Sheet explosive M186, M118 charge demolition		1.14
Military dynamite M1		0.92
Straight dynamite (commercial)	(40%)	0.65
	(50%)	0.79
	(60%)	0.83
Ammonia dynamite (commercial)	(40%)	0.41
	(50%)	0.46
	(60%)	0.53
Gelatin dynamite (dynamite)	(40%)	0.42
	(50%)	0.47
	(60%)	0.76
PETN		1.66
Tetryl		1.25
Composition B		1.35
Amatol 80/20		1.17
Black Powder		0.55
Nitrostarch		0.80
Pentolite		1.27

Foam Density

To determine the density of the foam, the foamer should be allowed to run at least 30 seconds. Then, a sample of the foam should be taken in a large, waterproof container. The expansion ratio is the weight of the container filled with water minus the weight of the empty container divided by the weight of the container filled with foam minus the weight of

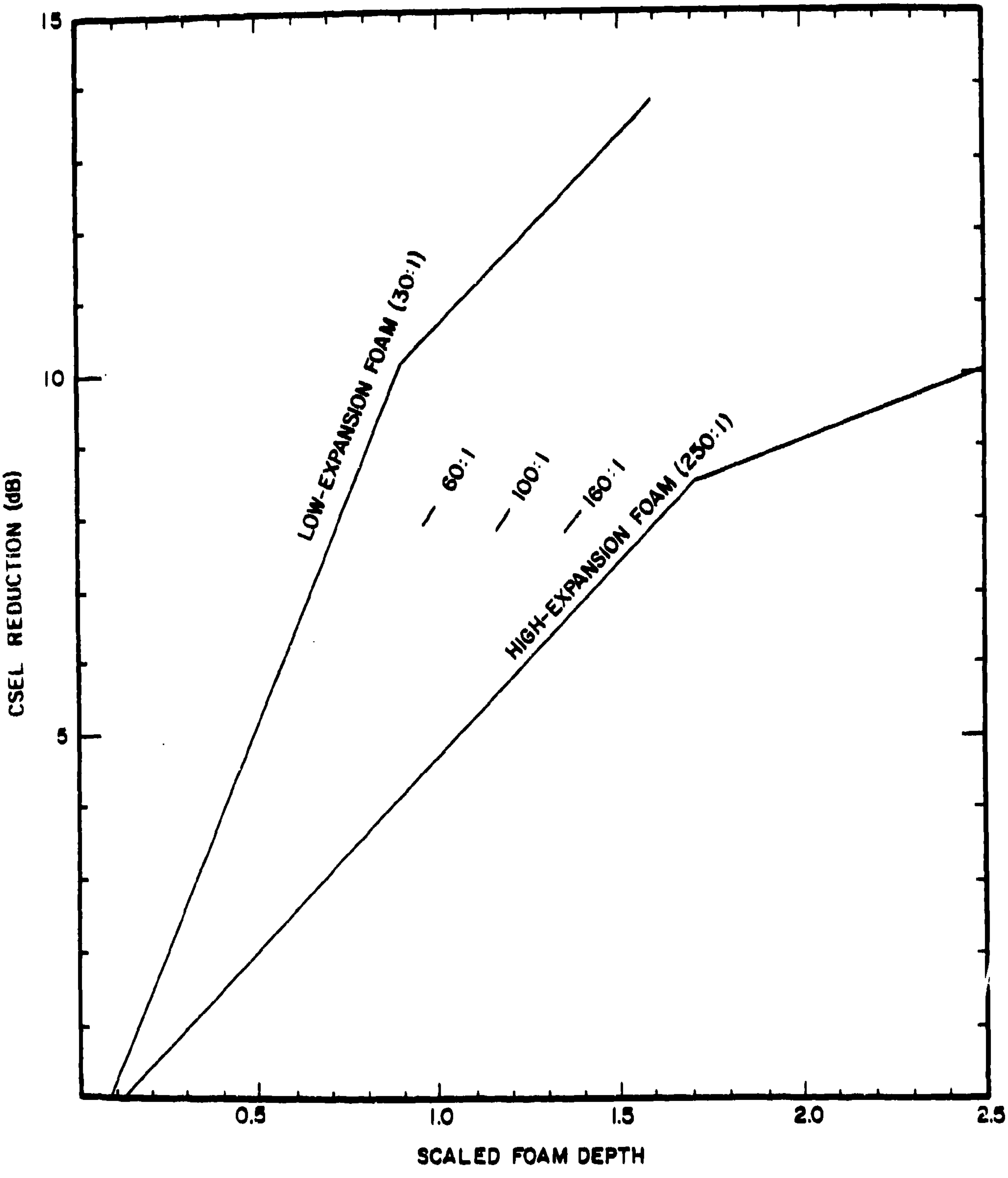


Figure 21. CSEL reduction prediction curves.

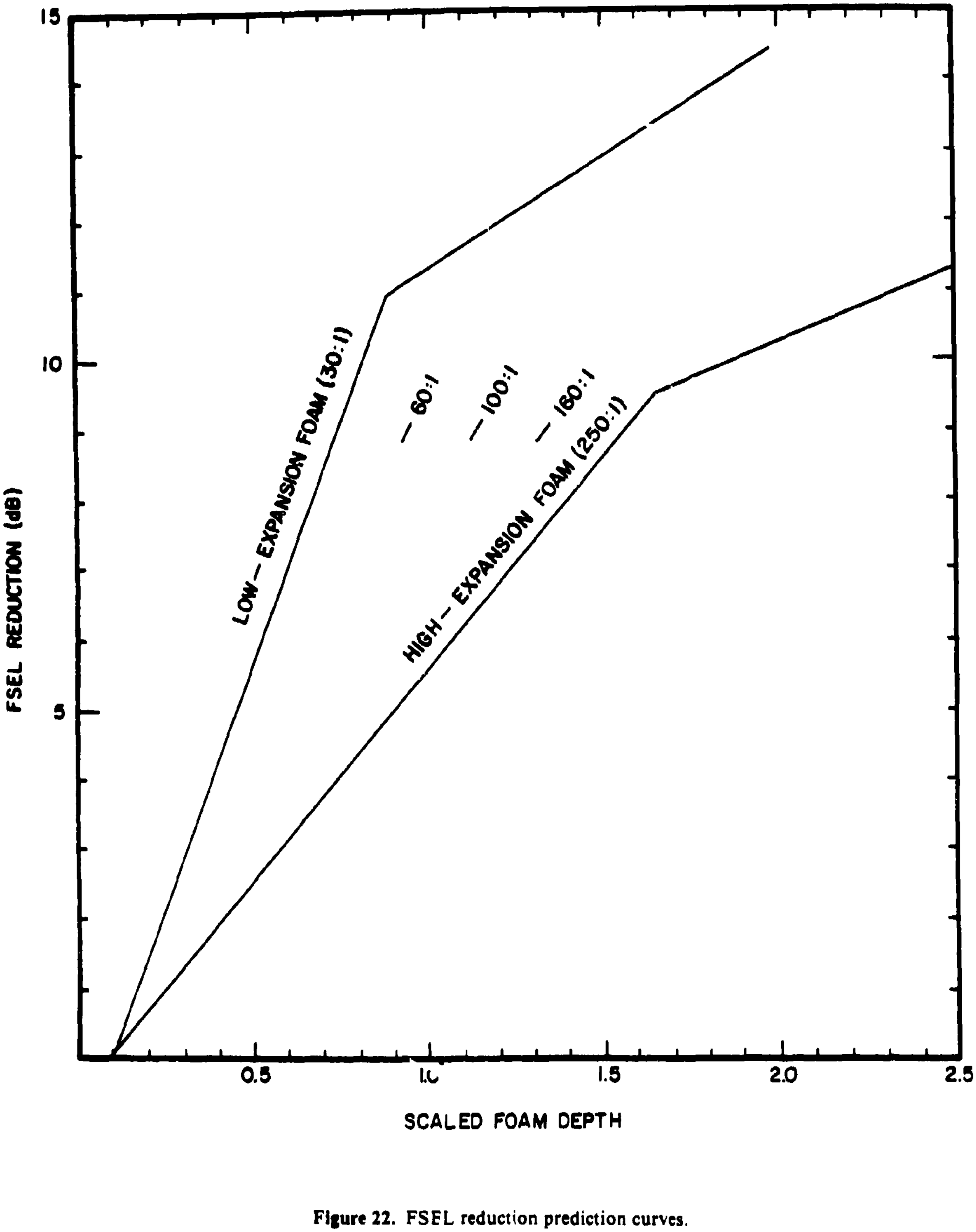


Figure 22. FSEL reduction prediction curves.

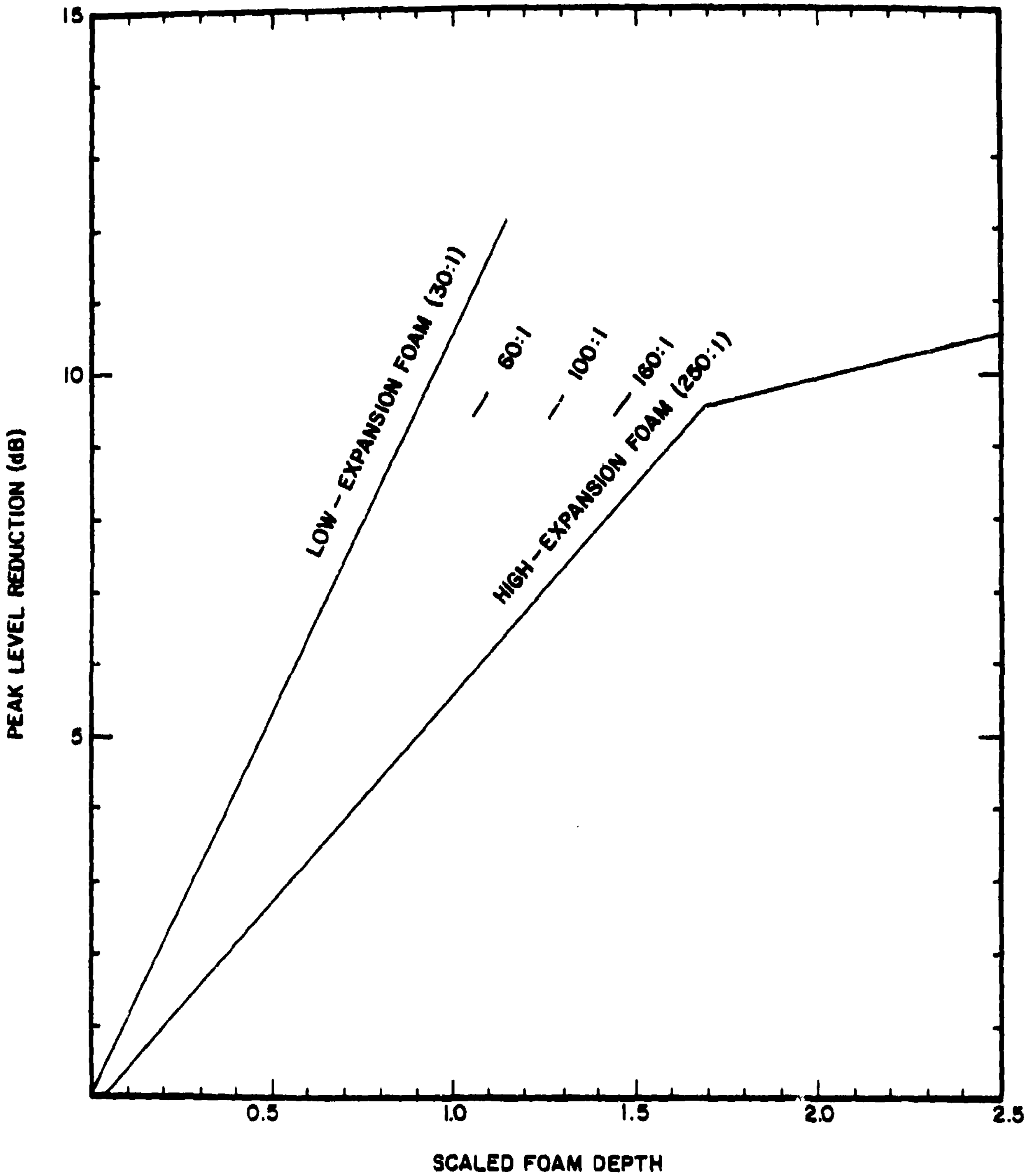


Figure 23. Peak level reduction prediction curves.

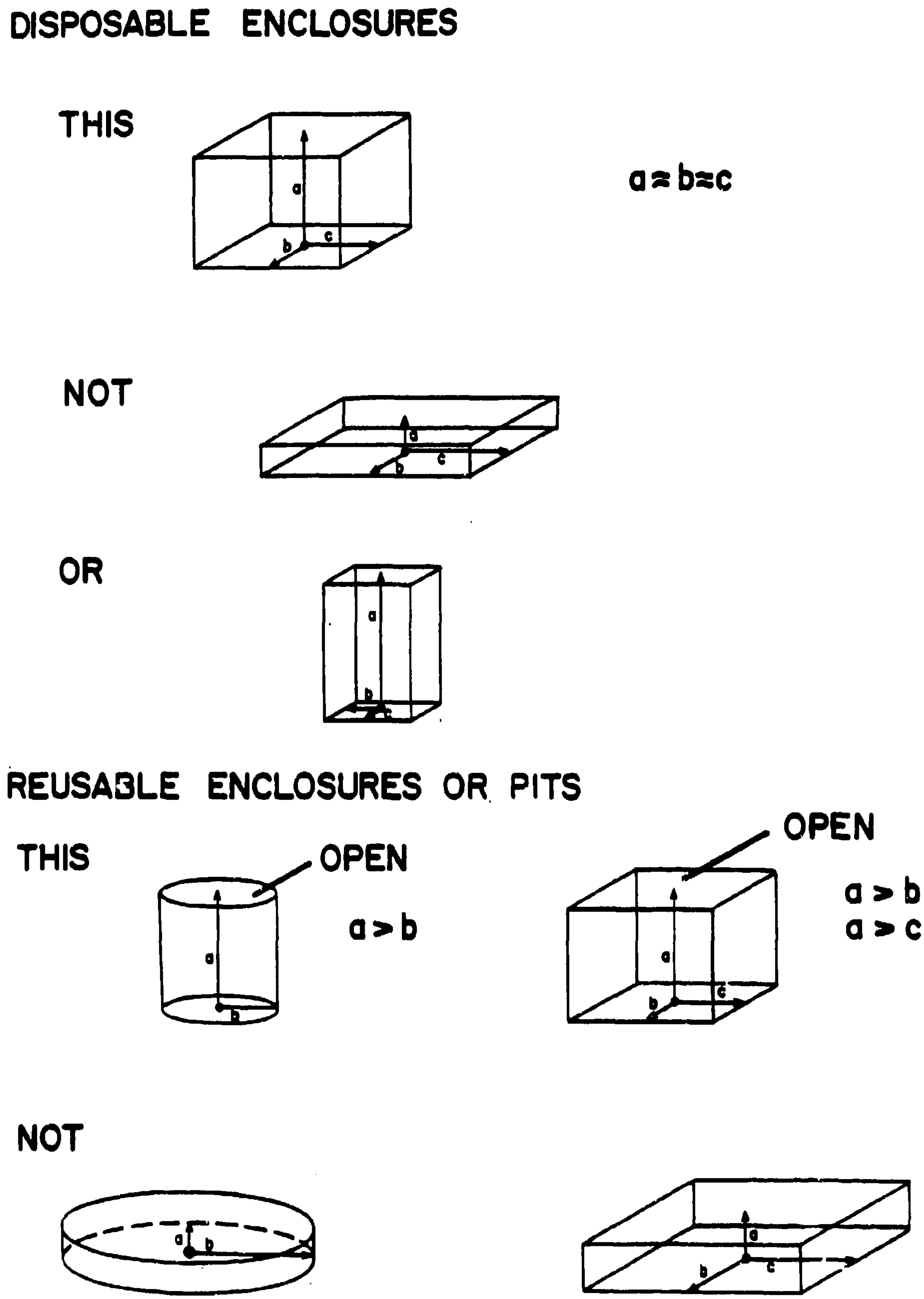


Figure 24. Sample foam enclosure designs.

Table 4

Common Demolitions and Their Equivalent Weights

Demolition	Explosive	Approximate TNT Equivalent
Demolition Kit, Bangalore Torpedo		
M1A1	4.1 kg Amatol 0.5 kg TNT booster	5.2 kg
M2A2	4.8 kg comp B4 0.5 kg A-3 booster	7.0 kg
Charge, demolition block, 40-lb cratering charge	13.6 kg ammonium nitrate 4.5 kg TNT	10.3 kg + booster charge
Charge: demolition: shaped		
(15-lb) M2A3	4.3 kg comp B 0.9 kg Pentolite	6.9 kg
(15-lb) M2A4	5.2 kg comp B 0.05 kg A3	7.0 kg
(40-lb) M3	12.8 kg comp B 0.8 kg Pentolite	18.3 kg
(40-lb) M3A1	13.8 kg comp B 0.05 kg A3	18.6 kg

the empty container. When collecting the sample, care should be taken to collect only foam and not liquid runoff:

$$\text{Expansion ratio} = \frac{\text{Weight of a volume of water}}{\text{Weight of the same volume filled with foam}} \qquad \text{[Eq 5]}$$

In this chapter, the expansion ratio is used when calculating reduction, although scaling was based on the foam density (Chapter 5).

Noise Level Reduction Calculation

To determine the noise level reductions produced by an unconfined or confined charge covered with foam:

1. Calculate the scaled foam depth:

$$\text{Scaled foam depth} = \frac{\text{foam depth}}{\sqrt[3]{\text{equivalent charge mass}}} \qquad \text{[Eq 6]}$$

2. Select the curve corresponding to the foam density (or the curve closest to the measured foam density). Figures 21 through 23 include hatchmarks corresponding to example foam densities. If the foam density is not 30:1 or 250:1, correct the foam depth to the nearer of the two curves:

a. For a foam closest to 30:1 with an expansion ratio less than 30:1, multiply the scaled foam depth by

$$\left(\frac{30}{\text{expansion ratio}}\right)^{1/3}$$

and determine the reduction from the appropriate 30:1 curve in Figures 21 through 23.

b. For a foam closest to 30:1 with an expansion ratio greater than 30:1, multiply the scaled foam depth by

$$\left(\frac{\text{expansion ratio}}{30}\right)^{1/3}$$

and determine the reduction from the appropriate 30:1 curve in Figures 21 through 23.

c. For a foam closest to 250:1 with an expansion ratio less than 250:1, multiply the scaled foam depth by

$$\left(\frac{250}{\text{expansion ratio}}\right)^{1/3}$$

and determine the reduction from the appropriate 250:1 curve in Figures 21 through 23.

d. For a foam closest to 250:1 with an expansion ratio greater than 250:1, multiply the scaled foam depth by

$$\left(\frac{\text{expansion ratio}}{250}\right)^{1/3}$$

and determine the reduction from the appropriate 250:1 curve in Figures 21 through 23.

Extrapolation below 30:1 and above 250:1 should be done with caution; foam above 250:1 does not give good results due to saturation.

3. Look up the reduction corresponding to the corrected scaled foam depth in Figures 21 through 23. This should be looked up on the line corresponding to the closest expansion ratio (as discussed in Step 2).

4. Correct for confined charges. If the foam is contained in an enclosure or pit which has walls which will not be knocked down by the explosion, the explosion is said to be confined. CERL's experiments indicate that if the change is confined, the reduction will be about 4 dB greater than if it is unconfined (Chapter 3).

General Guidelines

1. The largest reductions are achieved in relatively confined situations. Reduction should increase as the degree of confinement increases. Enclosures and pits with rigid walls that cannot be toppled by the explosion should be used, when possible.

2. The larger the charge, the more foam required. For very large charges, the enclosure size could become prohibitive. For example, to achieve a 10-dB reduction in CSEL for a 20-kg charge using a 30:1 foam in a pit or open-topped permanent enclosure would require an enclosure about 3 m on a side.

3. Although the low-expansion ratio foam produces higher ultimate attenuations, the capacity of commercial foamer units is limited to flow rates of 1.4 m^3/min. Higher expansion foamers generally need a larger foam volume to produce the same attenuation. However, these foamers have a very high flow rate (35 m^3/min). The decision as to which type of foam to use depends on the required enclosure size and the application time requirements.

Deployment Configurations

1. A reusable container should be considered for most field applications. These containers do not have to be rated to withstand the full charge, since even low-density foam will reduce blast overpressures by a factor of 5. An open-ended metal cylinder would make a good reusable container, since it is portable and suitably confining (Figure 25).

2. For training ranges and EOD, the charges can be set in a permanent pit on the range site (Figure 26)

3. For other applications, the foam can be deployed in a large plastic bag, a prototype of which was built and tested by CERL (Figure 27). The high-expansion foamer can produce a very dense foam when the foam is blown into the bag; it will take about 4 min to fill a 6 x 6 m bag with a 2 m high volume of foam.

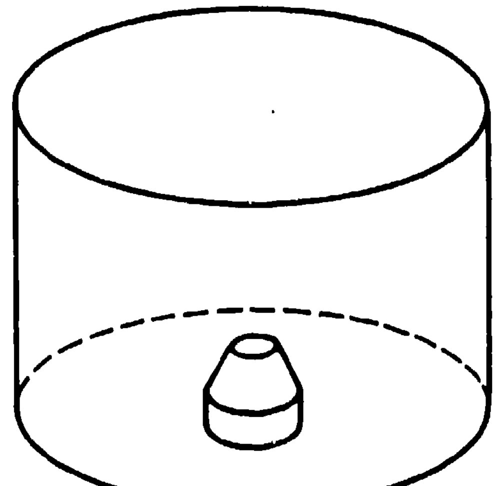


Figure 25. Example of portable foam enclosure.

7 THE USE OF AQUEOUS FOAM TO QUIET SHAPED AND CRATERING CHARGES

An important facet of Army engineer training is the use of shaped and cratering charges to create tank traps and other obstacles. These charges present environmental noise problems because they are among

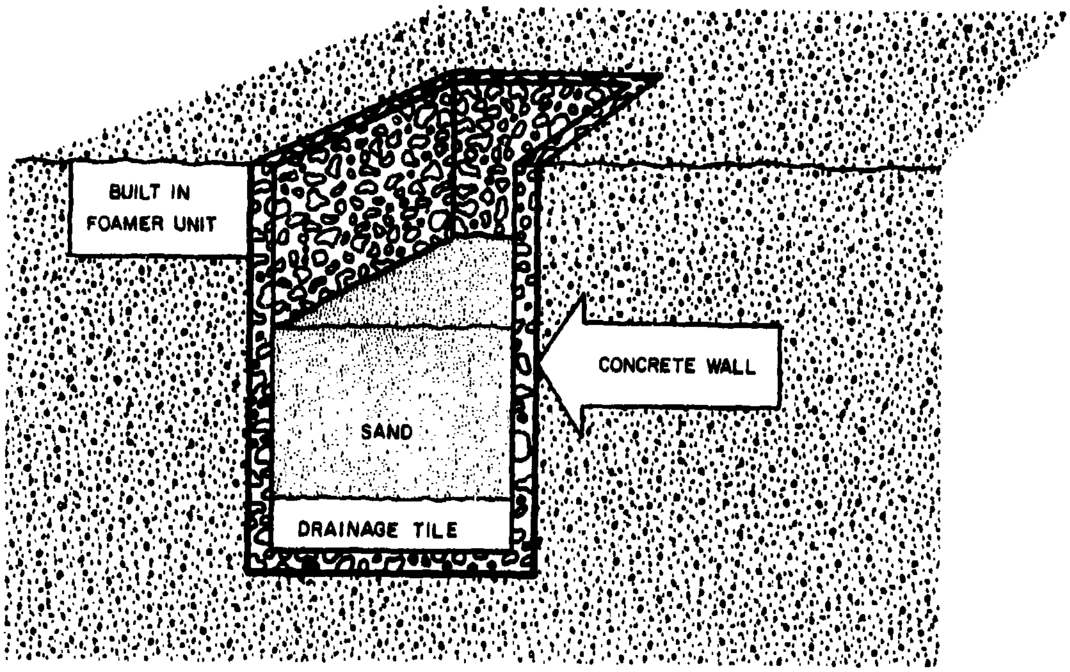


Figure 26. Example of a permanent foam enclosure configuration.

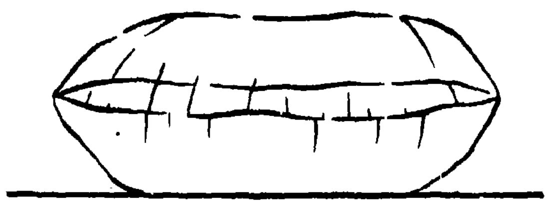


Figure 27. Example of a plastic bag type foam enclosure.

the largest charges routinely used for Army training. The characteristics of these charges are different from the bare charges used in the design work described in Chapters 3 through 6. The shaped charge is designed to direct energy into the ground to create a narrow, deep hole. The cratering charge is set underground and channels much of its energy into moving earth.

CERL investigated (1) the use of aqueous foam to quiet these charges and (2) whether the design charts developed for bare charges could be used with nonsymmetric charges like shaped and cratering charges.

Two types of charges were studied:

1. The M2A3 15-lb shaped charge. This charge is composed of 4.3 kg of Composition B and a 50-50 Pentolite booster weighing 0.9 kg in a fiber container. A cylindrical fiber base provides a 0.100 m standoff: a glass cone is used as a cavity liner.

2. A 40-lb cratering charge composed of 13.6 kg of ammonium nitrate-based explosives and a TNT-based explosive booster of 4.5 kg in the center portion next to the priming tunnels.

The cratering charges were set with a booster of 0.57 kg of C-4. In normal use, shaped charges are used to dig the holes in which the cratering charges are set. In the sandy loam soil at the test site, the shaped charge produced a hole about 2 m deep and 0.5 m wide.

Shaped Charges

Three configurations were evaluated in this experiment:

1. A 3.86 × 3.86 × 3.10 m high enclosure filled with high-expansion ratio foam (250:1).

2. A 1.73 × 1.73 × 1.52 m enclosure filled with low-expansion ratio foam (30:1).

Table 5

Reduction Results — Shaped Charge Tests

		Reduction (dB)		
Configuration	Foam Expansion Ratio	CSEL	FSEL	Peak
3.8 × 3.8 × 3.0 m	250:1	2.7	3.6	3.6
1.7 × 1.7 × 1.5 m	30:1	4.3	5.6	5.3
1.4 × 1.4 × 1.2 m	15:1	6.0	7.5	7.6

3. A 1.42 × 1.42 × 1.22 m high enclosure filled with low-expansion ratio foam (15.1).

All shaped charges were set at the standard standoff of 0.100 m so the top of each charge was 0.4 m above ground level. The experimental setup was the same as that used in the high-density foam tests (Chapter 3). Charges were set in pairs, one in the foam and one outside the foam. Microphones were placed on either side of the charges at 152 and 305 m. The CSEL, FSEL, and peak levels were measured on a CERL True-Integrating Noise Environmental Monitor and Sound-Exposure Level Meter. The signals were recorded on an Ampex 2230 14 Track FM recorder.

Results

Table 5 shows the reductions in CSEL, FSEL, and peak level measured for each experimental configuration. To check if the foam scaling laws could be used for shaped charges, the predicted reductions were calculated using the methods described in Chapter 6. (The calculation descriptions given below are presented step-by-step to allow the reader to calculate predictions for shaped charges with different foam densities and foam dimensions than the ones used in CERL's experiments.)

Configuration 1: 3.86 × 3.86 × 3.1 m (250:1 foam)

1. Calculate the equivalent charge mass, the foam depth, and the foam expansion ratio.

a. Equivalent charge mass: from Table 4, the equivalent charge mass for the M2A3 charge is 6.9 kg.

b. Foam depth:

$$\text{Foam depth} = \frac{(3.86 \times 3.86 \times 3.1)^{1/3}}{2} = 1.79 \text{ m}$$

c. Foam expansion ratio: in this case, the foam expansion ratio is 250:1.

2. Calculate the expected CSEL, FSEL, and peak level reductions:

a. Calculate the scaled foam depth:

$$\text{Scaled foam depth} = 1.79/(6.9)^{1/3} = 0.94 \text{ scaled m}$$

b. Locate the appropriate reduction prediction curves in Figures 21 through 23. In this case, the 250:1 prediction curves in Figures 21 through 23 indicate that for a scaled foam depth of 0.94 m, the CSEL, FSEL, and peak level reductions should be 4.4, 5.2, and 5.2 dB, respectively. Since the charges were unconfined, no correction is necessary.

3. Discussion: The curves predicted noise level reductions greater than the actual measured reductions of 2.5, 3.6, and 3.6 dB, respectively, for CSEL, FSEL, and peak level. Since only one trial was run for this configuration, the charge-to-charge variation could have produced errors this large. It is also possible that the reduction mechanism is not as effective for the directed energy of the shaped charge.

Configuration 2: 1.73 × 1.73 × 1.52 m (30:1 foam)

1. Calculate the equivalent charge mass, the foam depth, and the foam expansion ratio.

a. Equivalent charge mass: from Table 4, the equivalent charge mass for the M2A3 charge is 6.9 kg.

b. Foam depth:

$$\text{Foam depth} = \frac{(1.73 \times 1.73 \times 1.52)^{1/3}}{2} = 0.82 \text{ m}$$

c. Foam expansion ratio: in this case, the foam expansion ratio is 30:1.

2. Calculate the expected CSEL, FSEL, and peak level reductions:

a. Calculate the scaled foam depth:

Scaled foam depth $= 0.82/(6.9)^{1/3} = 0.43$ scaled m

b. Locate the appropriate prediction curves in Figures 21 through 23. In this case, Figures 21 through 23 indicate that the reductions in CSEL, FSEL, and peak level corresponding to a scaled foam depth of 0.43 scaled m should be 4.2, 4.6, and 4.5 dB, respectively. The foam was unconfined, so no correction is necessary.

3. Discussion: The predicted noise reductions agree reasonably well with the measured reductions of 4.3, 5.6, and 5.3 dB, respectively, for CSEL, FSEL, and peak level.

Configuration 3: 1.42 × 1.42 × 1.22 m (15:1 foam)

1. Calculate the equivalent charge mass, the foam depth, and the foam expansion ratio.

a. Equivalent charge mass: from Table 4, the equivalent charge mass for the M2A3 charge is 6.9 kg.

b. Foam depth:

Foam depth $= (1.42 \times 1.42 \times 1.22)^{1/3}/2 = 0.67$ m

c. Foam expansion ratio: in this case, the foam expansion ratio is 15:1.

2. Calculate the expected CSEL, FSEL, and peak level reductions:

a. Calculate the scaled foam depth:

Scaled foam depth $= 0.67/(6.9)^{1/3} = 0.35$ scaled m

b. Locate the appropriate prediction curves in Figures 21 through 23. In this case, the 15:1 expansion ratio is closest to and smaller than the 30:1 curve. To correct the foam depth, multiply by $(30/15)^{1/3}$:

Corrected foam depth $= 0.35 \times (30/15)^{1/3} = 0.44$ scaled m

Thus, from the prediction curves for the 30:1 expansion ratio in Figures 21 through 23, the reductions in CSEL, FSEL, and peak level should be 4.4, 4.7, and 4.7 dB, respectively. The foam was unconfined, so no correction is necessary.

3. Discussion: These predictions are lower than the measured values of 6.0, 7.5, and 7.5 dB, respectively, for CSEL, FSEL, and peak level.

Summary

Although each of the shaped charge measurements described above involved only one trial, limiting the accuracy of the results, it appears that for shaped charges denser foams produce larger reductions than predicted, and lighter foams produce less reduction than predicted.

In terms of the amount of water and detergent, the denser foams are more efficient. That is, it takes less water and detegent to produce a particular reduction with a dense foam than it does with the lighter foams.

To demonstrate what would be required to produce a particular reduction, a conservative estimate was made of the amount of 15:1 foam needed to reduce the peak levels of M2A3 shaped charges by 5 dB. In field use, a disposable cylinder would be a convenient way of providing support for the foam (Figure 25). The following describes how to calculate what size disposable cylinder would be needed to achieve a 5-dB reduction.

1. The scaled foam depth necessary to achieve a 5-dB reduction in peak level with the 30:1 foam is 0.47 scaled m (Figure 21).

2. To correct for the 15:1 foam expansion ratio, 0.47 scaled m is multiplied by $(15/30)^{1/3}$ (less foam is needed):

Corrected scaled foam depth $= \left(\frac{15}{30}\right)^{1/3} \times 0.47 =$ 0.37 scaled m.

3. To convert the scaled depth to the actual depth, 0.37 scaled m is multiplied by the cube root of the charge weight:

Depth $= (0.37)\,(6.9)^{1/3} = 0.70$ m

4. The cylinder dimensions must be sized so the cube root of the volume divided by 2 equals 0.70 m; the height should be larger than the diameter. In this

Table 6

Levels for Bare Cratering Charges

	304 m			152 m		
Depth (m)	CSEL	FSEL	Peak	CSEL	FSEL	Peak
1 0.76	107.2	109.5	123.2	111.6	119.7	134.7
2 0.74	113.3	119.2	137.8	120.8	126.6	145.9
3 0.97	97.9	108.9	123.9	107.6	117.0	131.2
4 0.61 wet	109.6	114.7	135.7	118.2	122.4	145.2
5 0.61 dry	112.2	116.6	138.6	119.8	123.6	146.1
6 0.97 dry	108.7	116.0	133.0	116.1	124.4	140.9
7 0.97 dry	98.8	102.6	124.4	108.6	117.9	137.4
Energy Average	109.4	114.9	134.5	116.9	122.8	142.8

Table 7

Comparison of Levels From Cratering Charges With Bare Charges

	304 m			152 m			
	CSEL	FSEL	Peak	CSEL	FSEL	Peak	
Average Level	109.4	114.9	134.5	116.9	122.8	142.8	Cratering Charges: Depth = 0.61 to 0.97 m in sandy loam
Loudest	112.2	116.6	138.6	119.8	123.6	146.1	
Average Level	114.5	117.1	138.7	122.8	125.5	148.2	0.567 kg of C-4, 0.6 m above ground
Average Level	118.8	123.0	145.0	127.7	131.7	153.2	2.27 kg of C-4, 0.6 m above ground

case, the cylinder should be 1.5 m in diameter and 1.65 tall.

Thus, it would take a 2.9 m^3 volume of 15:1 expansion ratio foam to reduce by 5 dB the peak noise level of a M2A3 shaped charge fired in a 1.5 m wide by 1.65 m tall cylinder. It would take 193 L (46 gal) of water and 9.7 L (2.3 gal) of foam solution to produce a 2.9 m^3 volume of 15:1 expansion ratio foam. At 1980 retail prices, this amount of foam detergent would cost less than $3.00. This amount of foam could be produced in 2 min with a single load of a Mearl OT 80-Dual 20 foamer.

Cratering Charges

An evaluation of whether foam can effectively quiet 40-lb (18-kg) cratering charges was not possible because of the variation in noise levels from charge to charge. Table 6 lists the levels of the cratering charge fired during CERL's experiments. The range of levels is more than 16 dB for all events. For matched pairs of events, where great care was taken as to identical depth and tamping, the variation was still as large as 14 dB. There appeared to be two groupings of charges by level. Events 1, 3, and 7 are low level, and Events 2, 4, 5, and 6 are about 10 dB louder on the average. However, the levels measured for even the loudest of these charges is still lower than the level that would be produced by a 0.57-kg charge fired in air (Table 7). Thus, as long as the cratering charges are buried to their design depth, single cratering charges will not produce environmental noise problems on ranges cleared for 0.57 kg charges.

8 THE USE OF AQUEOUS FOAM TO QUIET ARTILLERY

To investigate the potential of aqueous foam to quiet artillery, CERL conducted a joint study with the Ballistics Research Laboratory (BRL), Aberdeen Proving Ground, MD.

The gun used in the study was a 75-mm smooth bore weapon loaded with 2.5 kg of M-30 propellant. The projectile was a blunt-nosed slug. Microphones were placed at 53 m from the muzzle at 45 and 90° from the projectile line of flight. The blast signatures were analyzed *in situ* using the CERL True-Integrating Environmental Noise Monitor and Sound-Exposure Level Meter. Signatures were also recorded on Nagra SJ recorders. Measurements were made with the muzzle bare and compared to noise levels produced when the gun muzzle was inserted into various size foam containers. The foam densities used were 30:1 and 15:1.

Table 8 lists the CSEL, FSEL, and peak level reductions for various amounts of foam measured *in situ* during the CERL/BRL tests. These results show:

1. The reductions are greater to the front of the weapon. Since the foam containers were longer toward the front of the weapon, the greater reduction may be due to the longer path through the foam.

2. The 1.5-m mass of foam produced reductions in all metrics greater than 5.5 dB.

Table 8

Reduction in CSEL, FSEL, and Peak Level Measured *In Situ*

		45°			90°		
Event No.	Configuration	CSEL	FSEL	Peak	CSEL	FSEL	Peak
1	1.4 × 1.4 × 1.6 m (30:1)	6.8	7.3	9.4	3.2	4.4	4.4
2	1.5 × 1.62 × 2.3 m (30:1)	5.5	6.4	7.9	5.8	6.6	8.8
3	0.6 × 0.68 × 0.9 m (30:1)	3.2	3.4	2.9	1.2	2.5	2.9
4	0.6 × 0.68 × 0.9 m (15:1)	4.2	4.8	6.2	1.5	2.7	2.5
5	1.4 × 1.4 × 1.6 m (30:1)	5.9	6.1	5.1	5.3	5.1	4.3

Table 9

Reduction in FSEL and Peak Levels Measured Off the Tape Without Ballistic Wave and Echoes

Event No.	Configuration	45°		90°	
		FSEL	Peak	FSEL	Peak
1	1.4 × 1.4 × 1.6 m (30:1)	6.2	8.1	- 2.0	4.2
2	1.5 × 1.62 × 2.3 m (30:1)	6.1	8.1	5.2	7.3
3	0.6 × 0.68 × 0.9 m (30:1)	3.0	4.1	1.3	3.5
4	0.6 × 0.68 × 0.9 m (15:1)	4.4	4.5	1.7	3.7

Table 10

Average Levels of the Gun Without Foam

Station	CSEL	FSEL	Peak
45°	135.1	137.5	161.4
90°	133.1	135.3	158.9

3. The reductions increased with the amount of foam.

To check the effect of the ballistic wave, the data were edited so only the blast wave was measured from the tape. There was no general trend apparent in the differences as measured directly or from the tape (Table 9).

To develop foam scaling laws for artillery would require a much larger number of data points than those collected during the CERL/BRL study, since artillery blast waves are not spherically symmetric, and the optimum enclosure shape is also probably not spherically symmetric. However, the data *can* be related to the reduction prediction curves in Figures 21 through 23. For this relation, the following assumptions were made:

1. The shortest distance through the foam from the muzzle will be used as the foam depth. A lower bound for the predicted reduction is established by using the shortest distance.

2. Since the propellant charge is contained in the barrel, and much of the explosive energy goes into accelerating the projectile, the noise levels of artillery cannot be predicted from the charge weight alone. Instead of using the actual charge weight for scaling purposes, the weight of a bare charge which would produce the same noise level as the gun fired without foam has been employed. The levels measured at the 45 and 90° stations corresponded to base charges of 1.4 kg (at 90°) and 2.2 kg (at 45°). The average of these charge weights was 1.8 kg. Average noise level measurements of the gun without foam are given in Table 10.

3. The reductions scale as the cube root of the foam expansion ratios (as discussed in Chapter 6).

The data points are superimposed on the design charts in Figure 28 ("X" represents the 45° data, "+" the data taken at 90° to the muzzle).

From the plots it can be noted:

1. The data points cluster around the prediction lines, so the use of the prediction scheme developed by using explosives is at least qualitatively correct.

2. Extrapolating these results indicates that at least a 10-dB reduction can be achieved with unconfined foams. (The reductions should be larger if the foam is deployed in a cannister with rigid walls).

9 CONCLUSIONS

1. Both high- and low-expansion ratio foams can be used to reduce the blast noise of Army explosive charges. For unconfined explosions, blast noise can be reduced by up to 14 dB; if the explosion is confined, the foam's effectiveness is increased by about 3 to 6 dB.

2. It is possible to predict the blast noise level reductions for unconfined charges produced by different foams, foam depths, and charge masses.

3. It is possible to estimate the blast noise level reductions for confined charges produced by different foams, foam depths, and charge masses.

4. Aqueous foam can be used to reduce the blast noise levels of shaped charges and artillery.

5. Noise level reductions increase as the degree of confinement increases. The reduction properties of aqueous foam can be increased by deploying the foam in:

a. Enclosures or pits with rigid walls (for training range or EOD applications).

b. Reusable, portable metal cylinders (for field applications).

6. Foam density can be increased by deploying foam in plastic bags.

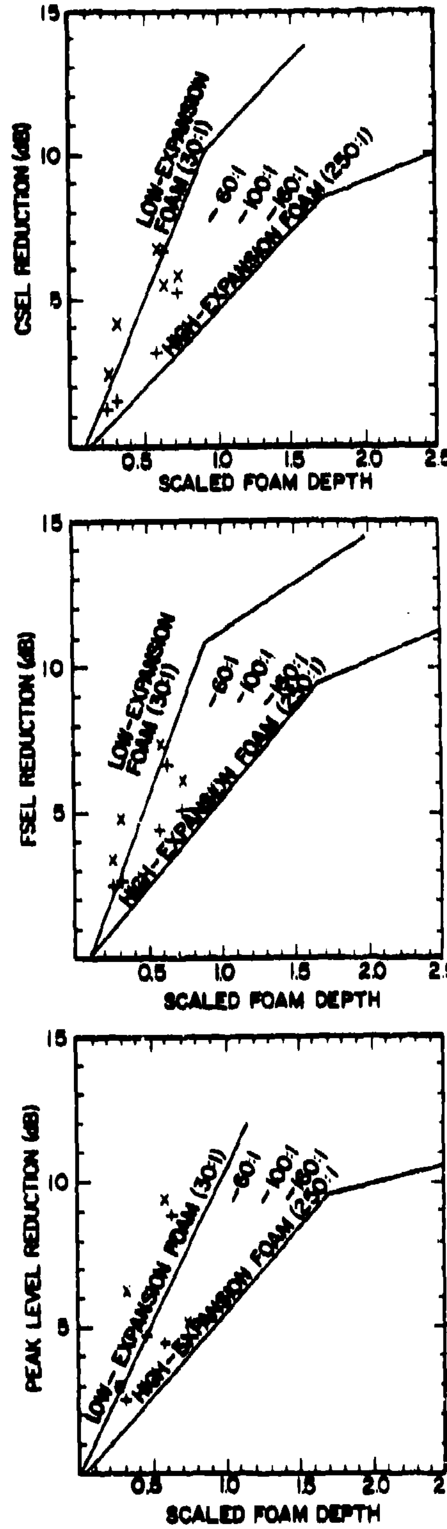


Figure 28. Artillery data points superimposed on CSEL, FSEL, and peak level reduction prediction curves.

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Division of Building Research
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